SCIENCE REVIEW OF

NASA CO-OP AGREEMENT NCC8-15

CHARACTERIZATION OF FLUID FLOW BY DIGITAL CORRELATION OF SCATTERED LIGHT

Presented at

George C. Marshall Space
National Aeronautics and Space
Marshall Space Flight
Huntsville, AL

by

John A. Gilbert, Ph.D.
Dept. of Mechanical Engineering
Univ. of Alabama in Huntsville
Huntsville, AL 35899
(205) 895-6029

Donald R. Matthys, Ph.D.
Physics Department
Marquette University
Milwaukee, WI 53233
(414) 224-1494

May 22, 1989

MEASUREMENT OF FLUID FLOW BY

DIGITAL CORRELATION

by

John A. Gilbert
Univ. of Alabama in Huntsville
Huntsville, AL 35899
(205) 895-6029

Donald R. Matthys
Marquette University
Milwaukee, WI 53233
(414) 224-1494

A. Possible Measurement Techniques

Various techniques are used for measuring two-dimensional fluid flow; the most general approach is to seed the fluid with microparticles and to illuminate the fluid with a thin planar sheet of laser light and then to record the speckle patterns obtained from the light scattered off the microparticles. The most common methods of analyzing the full-field data obtained are 1) Young's fringes, 2) Fourier filtering, and 3) digital correlation.

1) Young's Fringes

The Young's fringe technique can give the direction and magnitude of flow, but with an ambiguity in the sign of the flow direction. Although special means can be utilized to resolve the sign ambiguity, a more basic problem is that the technique cannot measure displacements smaller than the diameter of the microparticles seeded in the fluid, and if the particles are very small the scattered light intensity becomes weak. Also, the need for laser light to interrogate the specklegram containing the image data introduces secondary speckle into the Young's fringes being measured and limits the accuracy with which their positions can be determined.

2) Fourier Filtering

This measurement method gives a full field measurement immediately, but only of a particular component of the velocity vector. To obtain more information about the fluid flow, the velocity selecting aperture must be moved radially and tangentially around the center of the diffraction halo produced by the speckle pattern being studied in the transform plane. The need for laser illumination introduces secondary speckle which, if the aperture is kept small to select a narrow frequency range, makes the fringes in the filtered image difficult to read.

3) Digital Correlation

This technique does not need to use laser light on the speckle pattern, so no secondary speckle is introduced. Also, the lower limit of displacement measurement is determined by the resolution of the sensor used and the magnification of the camera, and can be much lower than the speckle size, so a considerably wider range of measurement is possible than with the other methods. Also, since no mechanical scanning of the image is required, the technique is potentially much faster than the other methods.

B. Demonstration of the Advantages of the Digital Correlation Technique

Test cells of various configurations and sizes were built and filled with seeded fluids to demonstrate the viability of digital correlation as a method for obtaining fluid velocity fields. Preliminary tests were run on different liquids (water, ethylene glycol) seeded with particles of different sizes (2, 8, 15, and 50 micron diameter plastic spheres) to determine suitability. A novel method of correlating a series of image pairs so as to obtain the effect of heavy seeding from what is actually a light seeding was developed and validated by first testing the method on a set of images of simulated data and then by measuring the actual flow in a test cell filled with water that had been seeded with 15 micron spheres. This ability to use a time series of images means that the investigator can work with images selected from the whole set to obtain more detailed information in regions of particularly high or low velocity; also, if the images were stored on film, it is possible to magnify selected regions of interest for high resolution analysis, down to the resolution of the film and camera system.

Since correlation depends on randomness in the data, it might be thought that collating sets of image pairs for analysis would introduce a patterned structure into the image and lead to spurious results, but by using aperiodic time intervals between image pairs, any periodicity can be eliminated. Excellent results were obtained and the investigators claim that the digital correlation technique has significant advantages in the range of velocity measurements possible and the speed and accuracy with which results can be obtained.

Proposal for Continuation of NASA Co-op Agreement NCC8-15

CHARACTERIZATION OF FLUID FLOW BY DIGITAL CORRELATION OF SCATTERED LIGHT

John A. Gilbert, Ph.D.
Univ. of Alabama in Huntsville
Huntsville, Alabama 35899

Donald R. Matthys, Ph.D.
Marquette University
Milwaukee, Wisconsin 53233

1. Introduction

This proposal requests funding for the second year of a three-year proposal which has already been funded for its first year. A copy of the original proposal is appended to the present proposal. The objective of the study is to produce a physical system suitable for a space environment that can measure fluid velocities in a three-dimensional volume by the development of a particle correlation velocimetry technique. The basic concept of this technique is to follow the movement of particles in the fluid by computing correlations between speckle images separated in time.

The tasks and objectives of the first year of the proposal have been attained in accordance with the schedule given in the original proposal. Progress made to date is described below.

2. Progress to Date

The proposed plan for the first year was to conduct experimental studies on a fluid test cell to demonstrate the suitability and accuracy of digital correlation techniques for measuring two-dimensional fluid flow. The tasks specified for the first ten months were to assemble and test computer hardware and software, to design an appropriate illumination and detection system for making velocity measurements within a test cell, to design and construct a test cell, to make preliminary evaluations on fluid and seeding requirements, and to enhance the software techniques for 2-D analysis of fluid flow.

The hardware platform selected to meet the computational requirements was the 80386 microprocessor running on the standard AT bus under a UNIX multiuser operating system. In addition, the computer can also run under standard MS-DOS allowing access to a wide range of commercially available image acquisition and analysis programs. Equipment acquisition included additional monitors for image display of the scattered light speckle patterns and laser printers to enable high resolution graphics output.

A 10 milliwatt HeNe laser and suitable optics were obtained to illuminate selected planes in the fluid volume. The acquisition of speckle pattern images is handled by a sensitive CCD camera with 512 x 512 resolution and with

an electronic shutter which offers the capabilities of synchronization, strobing, and temporal integration.

The correlation routines mentioned in the original proposal were ported to the new computer system and were enhanced to take advantage of the larger memory capacity of the 80386. New graphics packages were obtained to display output at higher resolution.

To develop appropriate fluid cells suitable for the present study, the investigators visited various fluid dynamics laboratories (including AT&T Bell Laboratories in Murray Hill, New Jersey and the Fluid Dynamics Laboratories at the Illinois Institute of Technology in Chicago) and consulted with other researchers on the impact of various design parameters for optimizing specific experimental tasks. Three fluid cell were designed and an appropriate pump obtained to produce controlled flow distributions. Preliminary work was begun on the selection of proper fluids and seeding particles. Water and ethylene glycol were selected for preliminary evaluation based on properties of transparency, viscosity, density, and index of refraction. Plastic microspheres of various diameters (2, 7, 15, and 50 micron) with a density and refractive index compatible with the aforementioned fluids were selected. Work has begun to evaluate the effects of different diameters and different seeding densities in the fluid test cell.

A new method for correlating multiple exposures was developed and validated, first on simulated data, and then on real data obtained by capturing images of seeded fluids flowing through a test cell.

3. Tasks and Objectives for the Second Year

In the second year a working system for two-dimensional velocimetry will be produced and an appropriate method selected for making three-dimensional measurements. The tasks and objectives proposed here for the second year are unchanged from the description given in the original three-year proposal, from which the following description is abstracted.

Second Year:

Goal: Produce a working system for two-dimensional velocity measurements and select an appropriate method for making three-dimensional measurements.

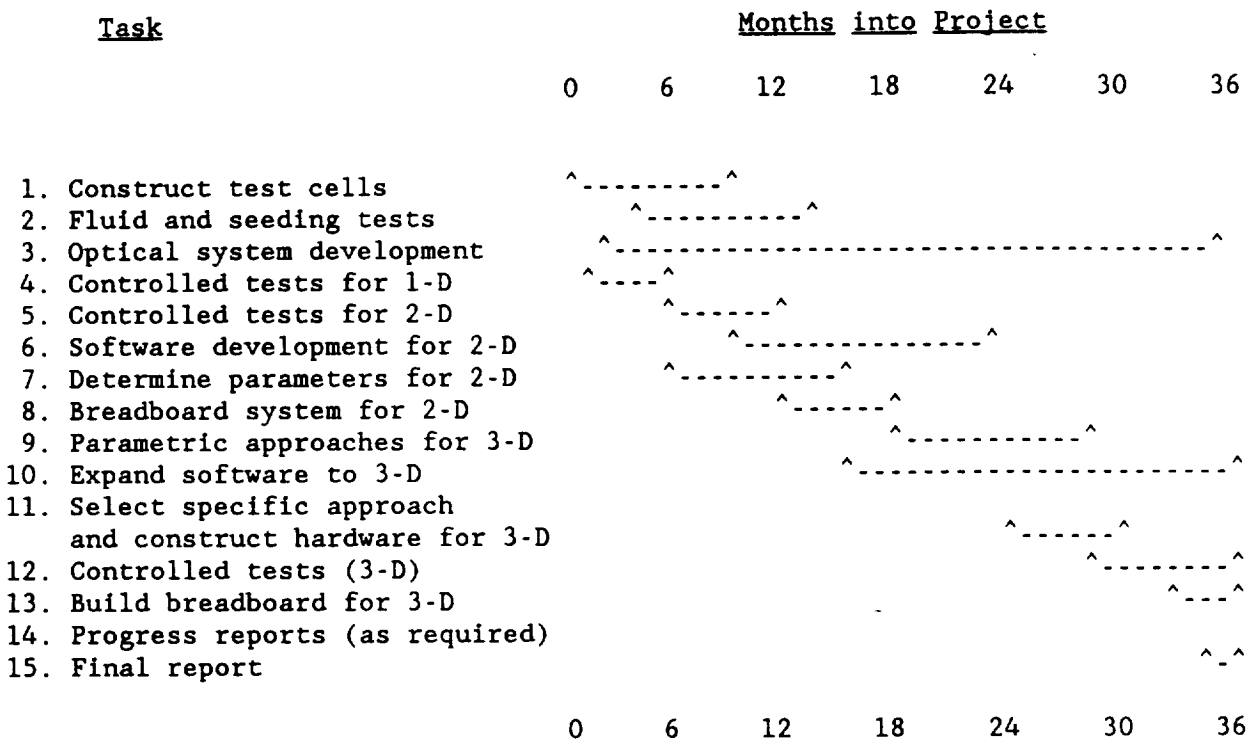
1. Consolidate hardware and software into a breadboard system that will measure fluid flow parameters in two-dimensions.

2. Perform evaluative tests and parametric studies of the different approaches for obtaining three-dimensional data.

3. Revise software to characterize a three-dimensional velocity field.

These tasks are scheduled according to the original timetable, a copy of which is shown in the following timetable.

4. Timetable for the Total Three-Year Project



5. Conclusion

The researchers feel that work on the project is on schedule and that the goals and objectives of the first year have been satisfactorily achieved. They therefore request funding for the project be continued through its second year phase in accordance with the attached budget.

FLUID FLOW MEASUREMENT

BY

DIGITAL CORRELATION

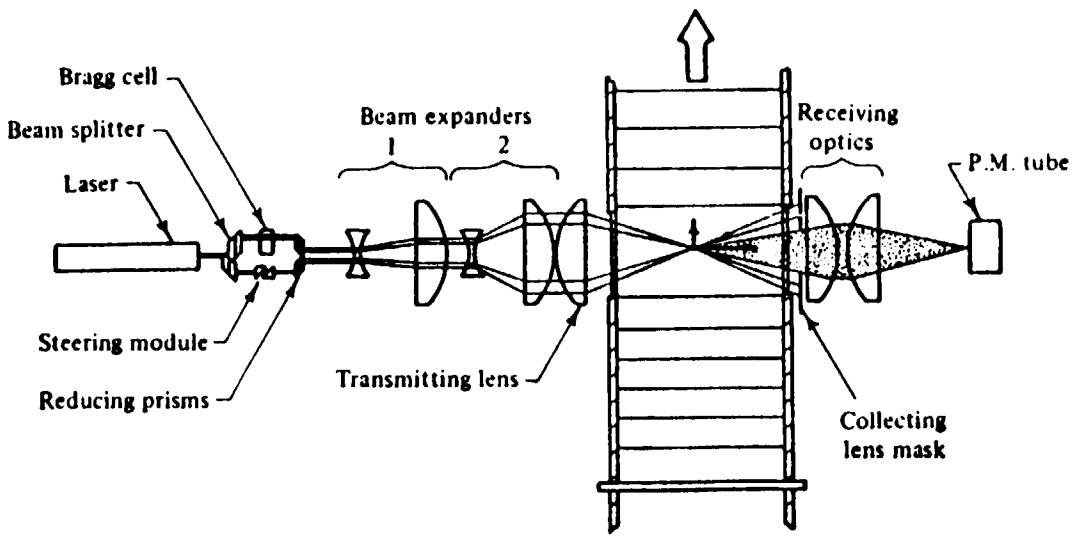
JOHN GILBERT
UNIV. OF ALABAMA IN HUNTSVILLE
HUNTSVILLE, AL 35899

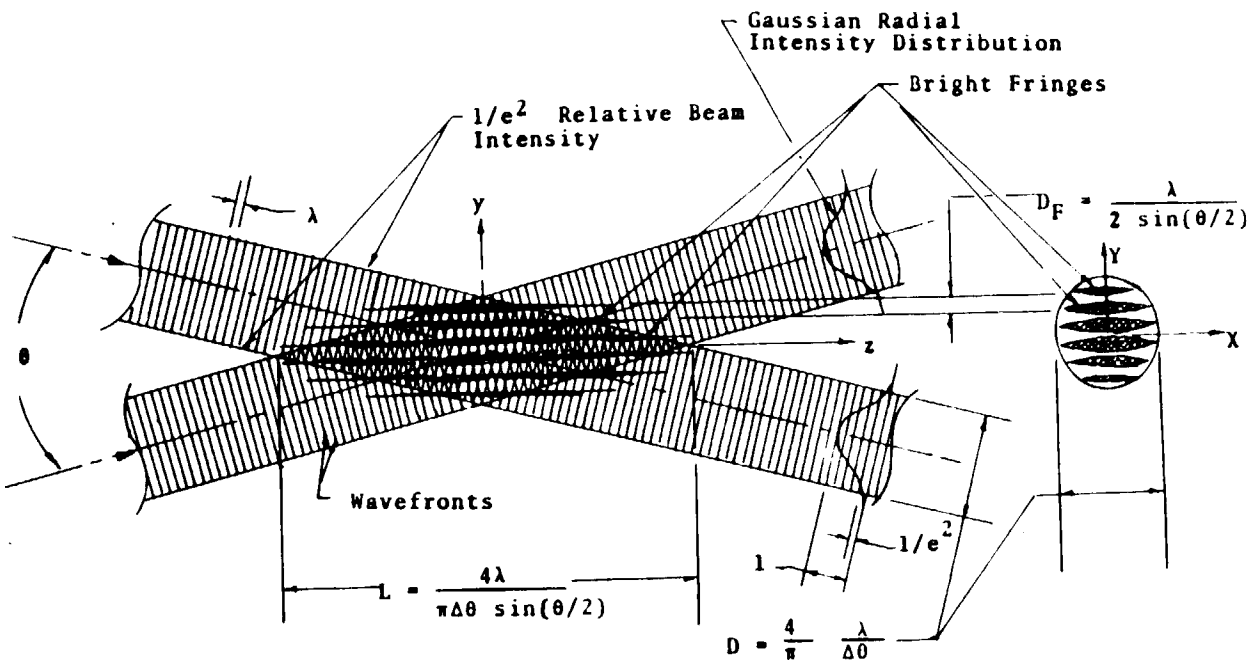
DONALD MATTHYS
MARQUETTE UNIVERSITY
MILWAUKEE, WI 53233

LASER SPECKLE VELOCIMETRY

- LASER DOPPLER VELOCIMETRY
- YOUNG'S FRINGES
- FOURIER FILTERING
- DIGITAL CORRELATION

LASER DOPPLER VELOCIMETRY


Bragg cell
Beam splitter
Laser
Steering module
Reducing prisms
Beam expanders
1
2
Transmitting lens
Receiving
optics
P.M. tube
Collecting
lens mask



BEAM CROSSOVER REGION OF AN LDV SETUP

$$f_D = (2v_y/\lambda)\sin(\theta/2)$$

THE FREQUENCY AT WHICH LIGHT INTENSITY IS MODULATED

LASER DOPPLER VELOCIMETRY

vs.

LASER SPECKLE VELOCIMETRY

LDV MEASURES "TIME HISTORY" OF VELOCITY COMPONENT(S) IN LOCAL "SAMPLE VOLUME"

LSV MEASURES FIELD OF IN-PLANE VELOCITY IN "SAMPLE PLANE" AT ONE "INSTANT IN TIME"

LASER SPECKLE VELOCIMETRY

LASER SPECKLE VELOCIMETRY

INTRODUCTION
- CONCEPT
- RELATED TECHNIQUES
- ORIGINS OF LSV

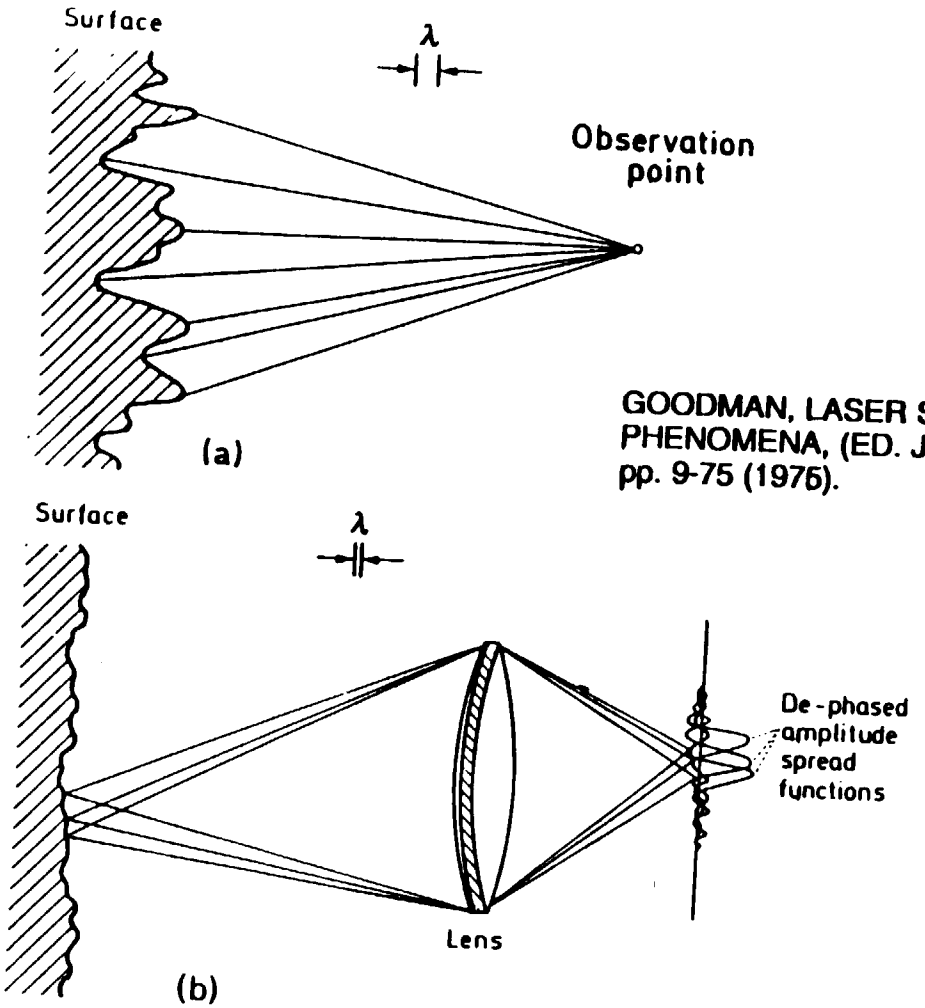
SEEDING
- MATERIALS
- CONCENTRATION

ILLUMINATING SHEET
- LASER SOURCE
- BEAM SHAPING OPTICS
- GEOMETRY

SCATTERED LIGHT RECORDING
- OPTICS
- EXPOSURES
- MEDIA

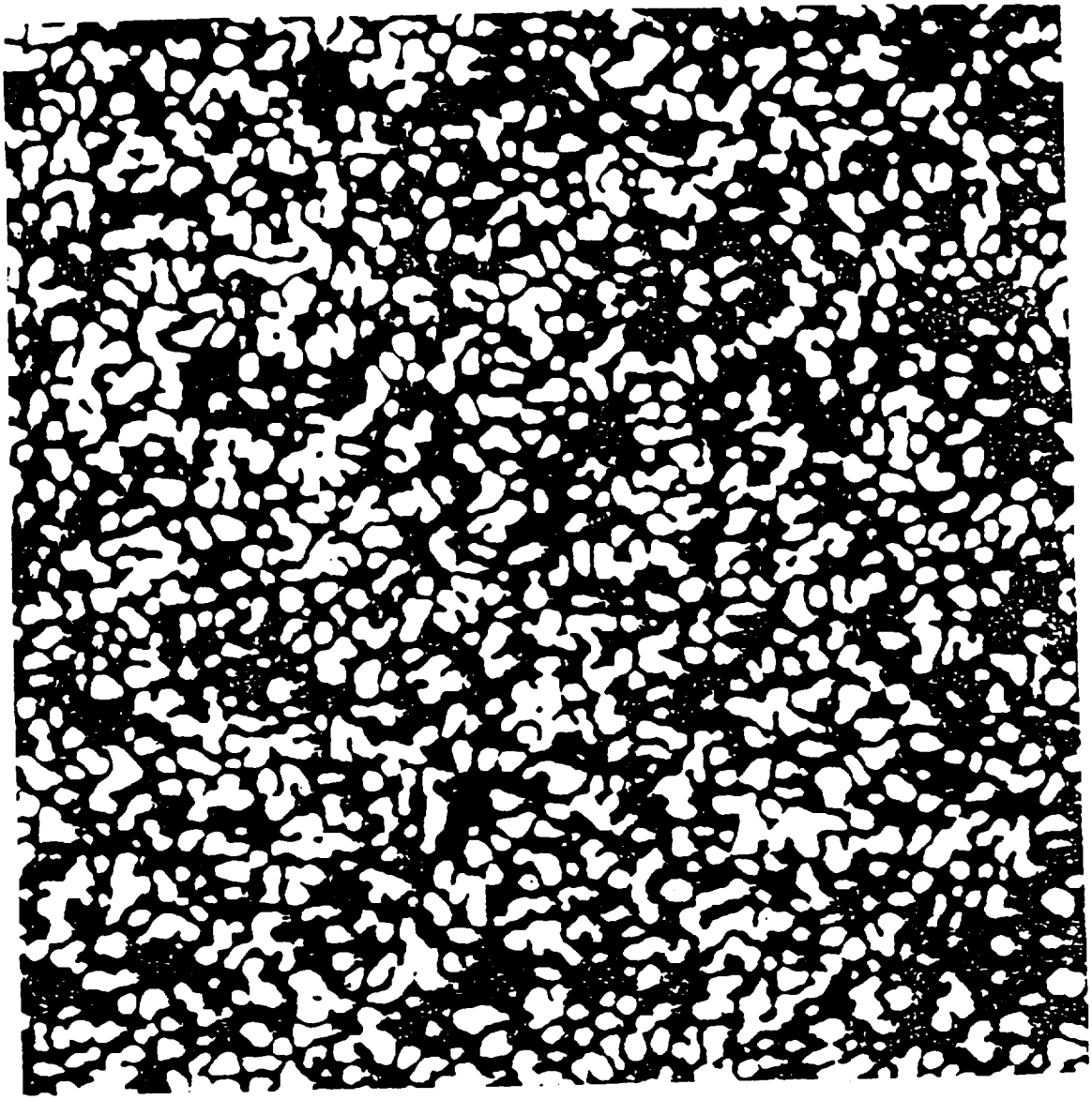
SPECIAL TOPIC
- RESOLVING THE SIGN AMBIGUITY

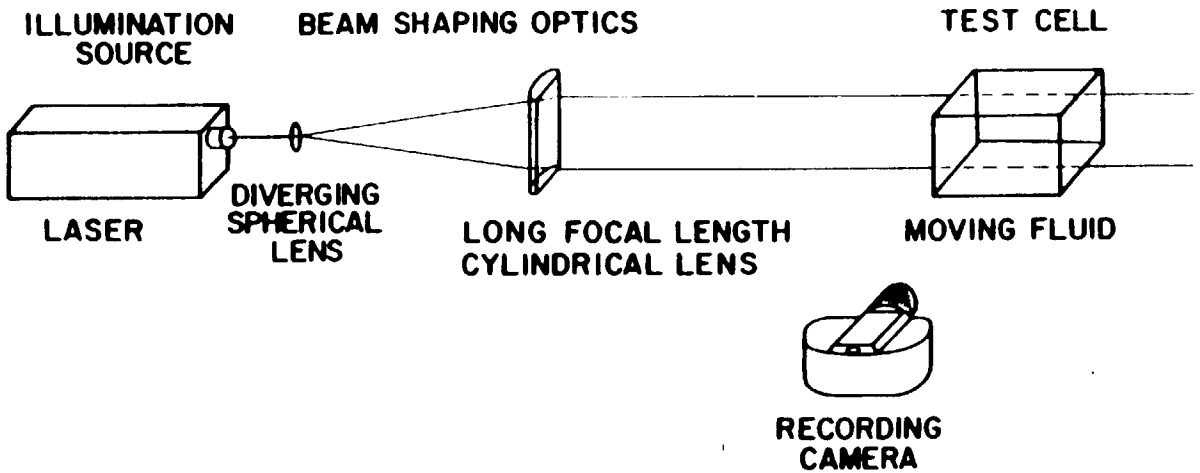
APPLICATIONS
- COHERENT SPECKLE DOUBLE EXPOSURE
- PARTICLE IMAGE DOUBLE EXPOSURE
- PARTICLE IMAGE MULTIPLE EXPOSURE
- DIGITAL CORRELATION METHODS



GOODMAN, LASER SPECKLE & RELATED PHENOMENA, (ED. J.C. DAINTY), SPRINGER pp. 9-75 (1975).

Physical origin of speckle for (a) free-space propagation, (b) an imaging system




ILLUMINATION SOURCE
BEAM SHAPING OPTICS
TEST CELL
LASER
DIVERGING SPHERICAL LENS
LONG FOCAL LENGTH CYLINDRICAL LENS
MOVING FLUID
RECORDING CAMERA

LSV
SCATTERED LIGHT PATTERNS

GENERATED BY EITHER:

- INTERFERENCE SPECKLE OF CHARACTERISTIC SIZE

$$\sigma = 1.2\ \lambda F(1+m)$$

OR

- PARTICLE IMAGES OF UNIFORM DIAMETER

$$d_i = (m^2 d^2 + d_s^2)^{1/2}$$

WHERE:

- m = MAGNIFICATION
- λ = WAVELENGTH
- F = f – NUMBER OF IMAGING LENS
- d_s = DIFFRACTION LIMITED SPOT DIAMETER OF IMAGING LENS
- d = SCATTERING PARTICLE DIAMETER

LASER SPECKLE VELOCIMETRY MODES

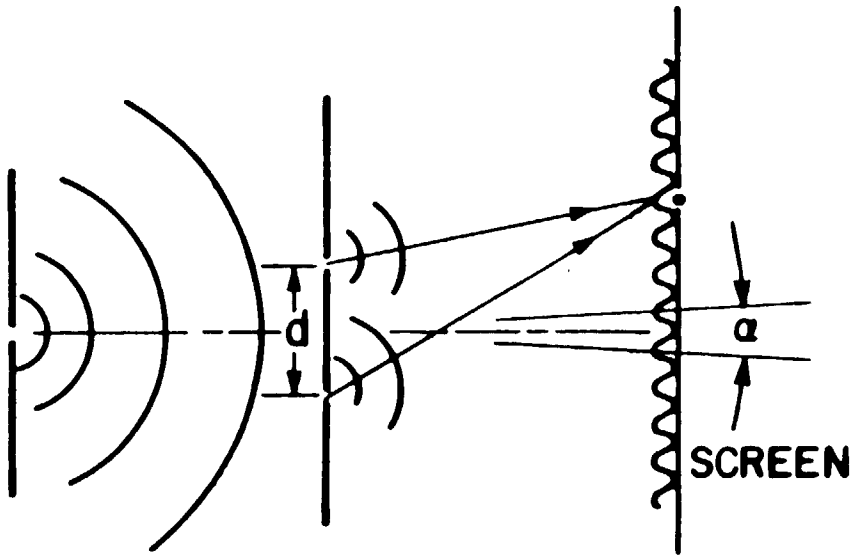
COHERENT (INTERFERENCE) SPECKLE

- HIGH SEEDING CONCENTRATION
- COHERENT PROPERTY OF ILLUMINATION MATTERS

PARTICLE IMAGE

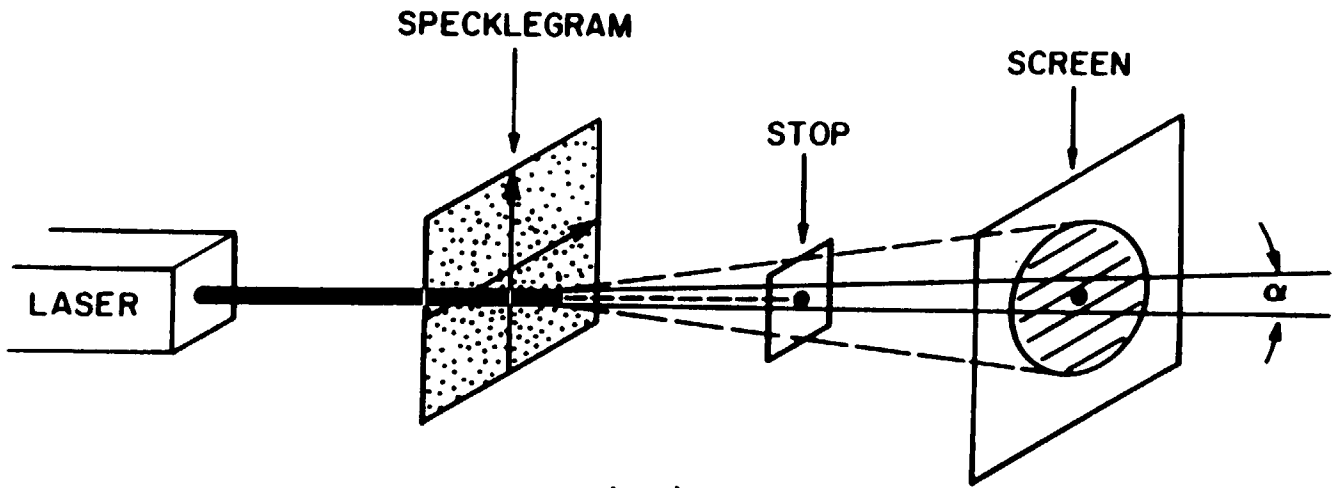
- LOW SEEDING CONCENTRATION
- COHERENT PROPERTY OF ILLUMINATION DOES NOT MATTER
- USE POSITIVE IMAGE TRANSPARENCY

YOUNG'S FRINGE ANALYSIS

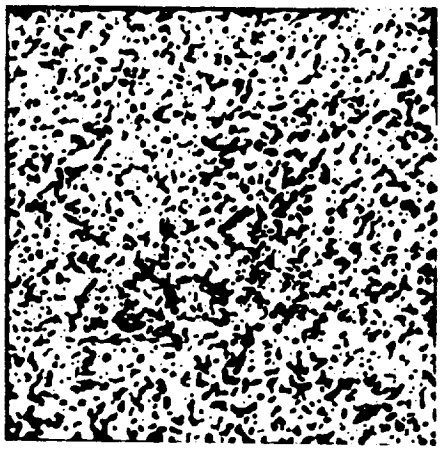


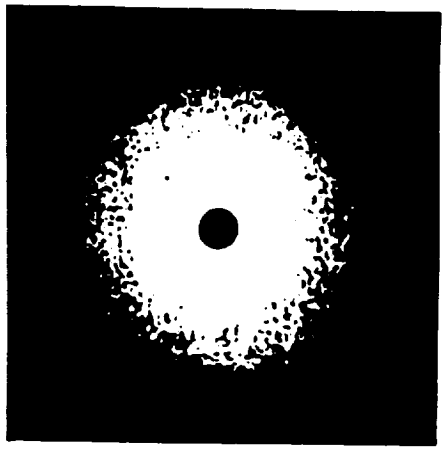
$\sin\alpha = \lambda / d$

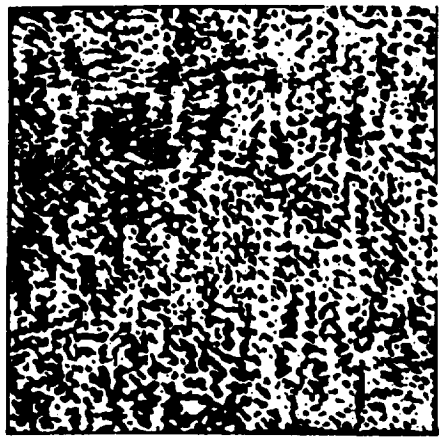
YOUNG'S EXPERIMENT (1802)

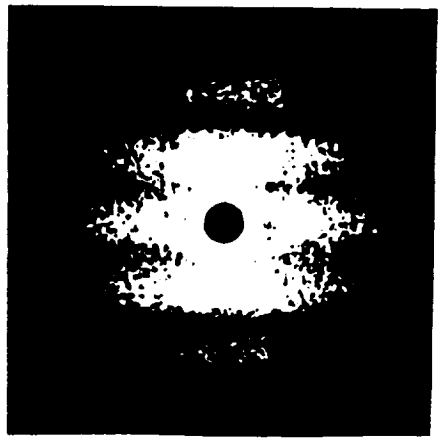


$$d = \lambda / (m \sin \alpha)$$

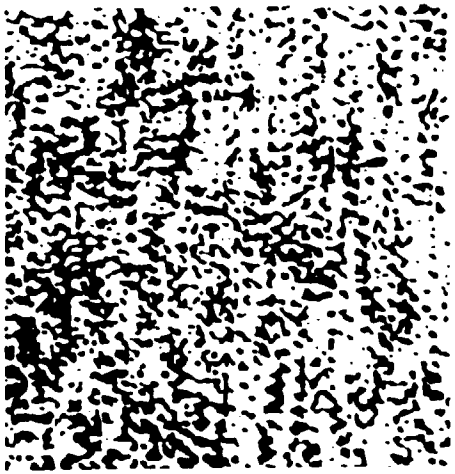


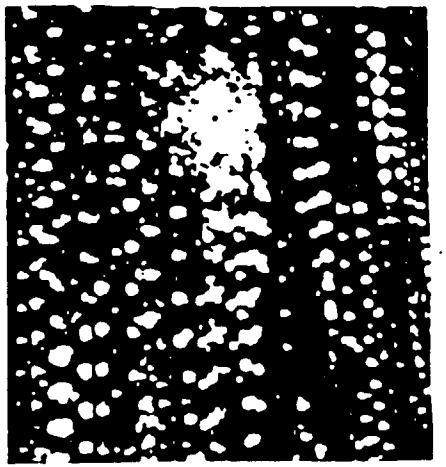






SPECKLE PHOTOGRAPH (MAGNIFIED)

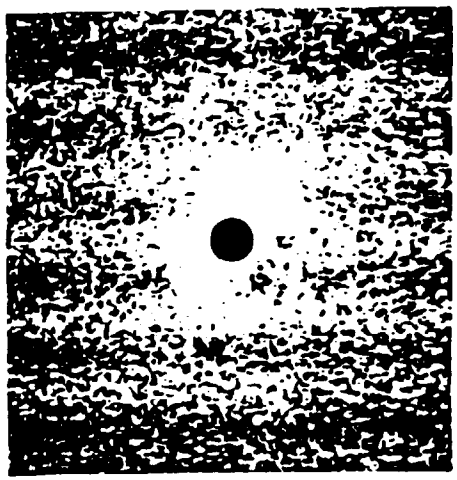


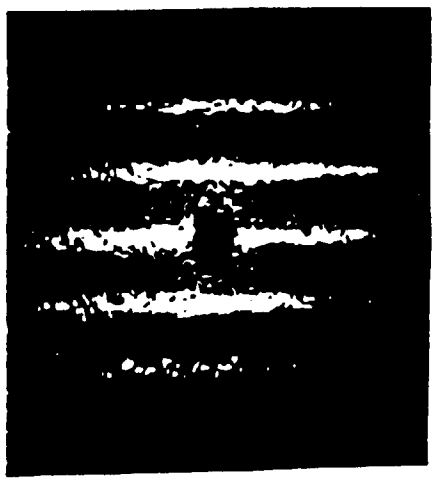


DOUBLE EXPOSURE

MULTIPLE EXPOSURE

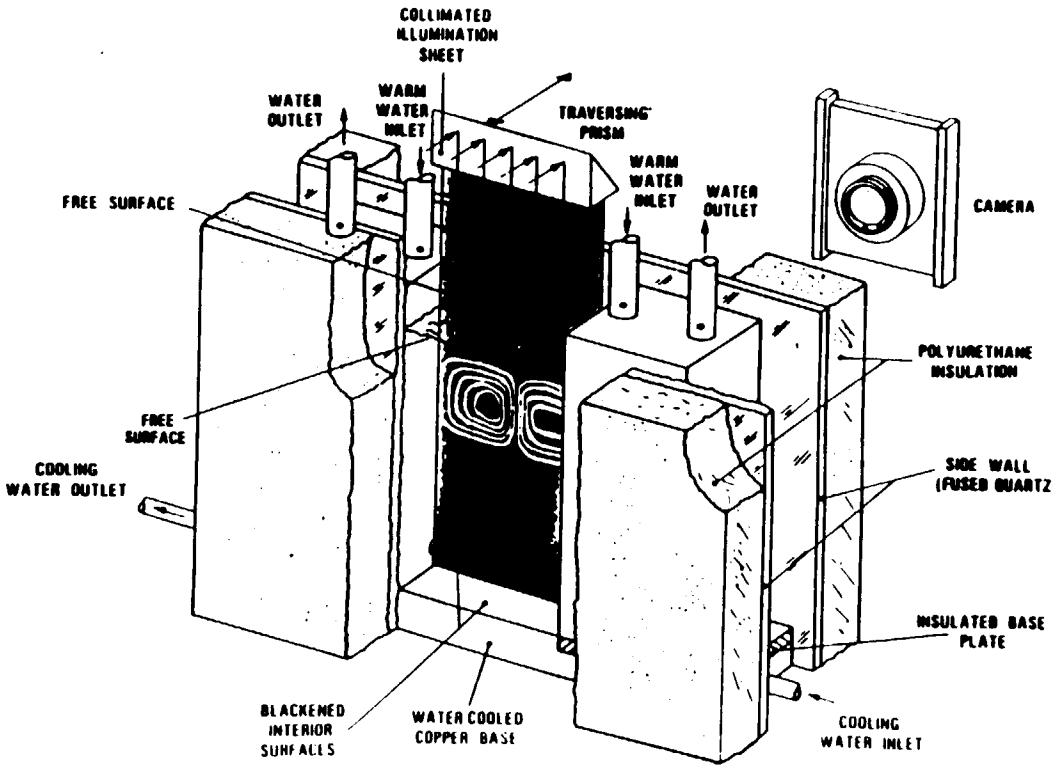
YOUNG'S FRINGE FIELD

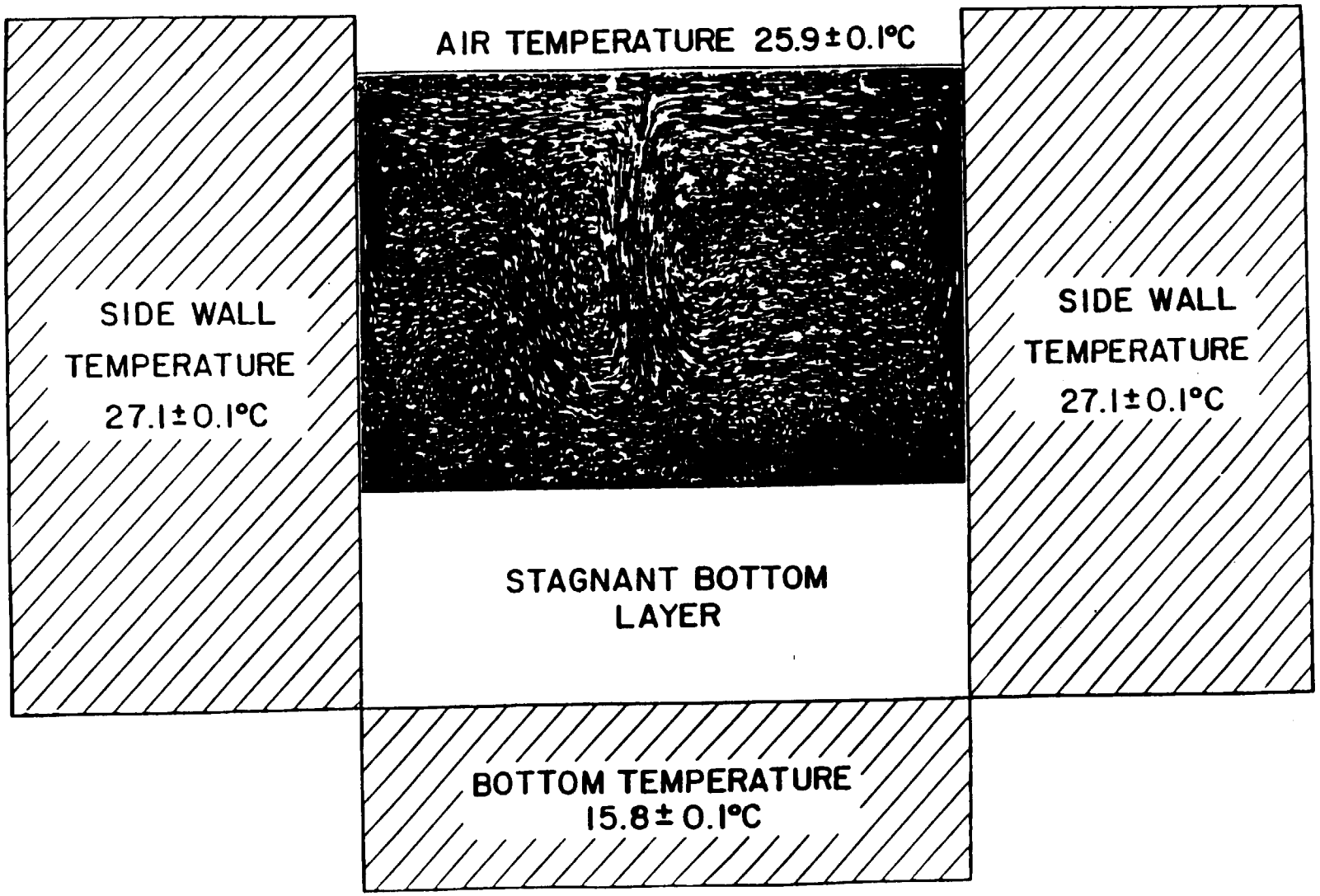


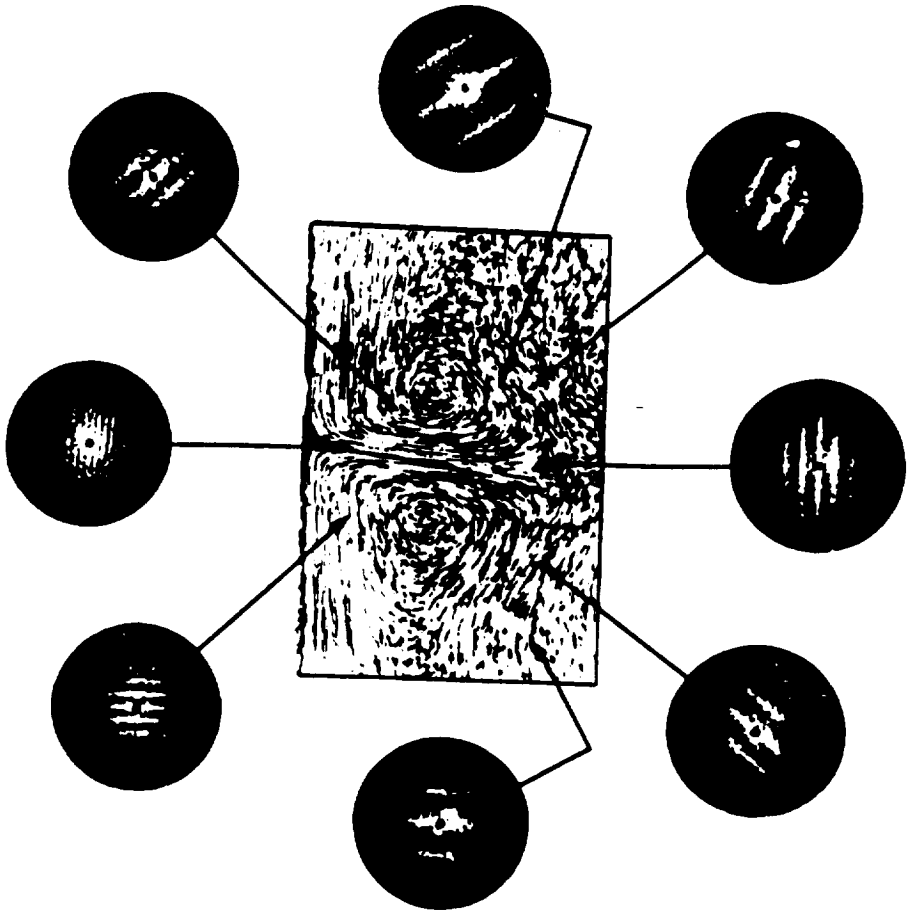


LASER SPECKLE VELOCIMETRY APPLICATION

DESCENDING PLUME




AIR TEMPERATURE 25.9±0.1°C
SIDE WALL
TEMPERATURE
27.1±0.1°C
SIDE WALL
TEMPERATURE
27.1±0.1°C
STAGNANT BOTTOM
LAYER
BOTTOM TEMPERATURE
15.8±0.1°C

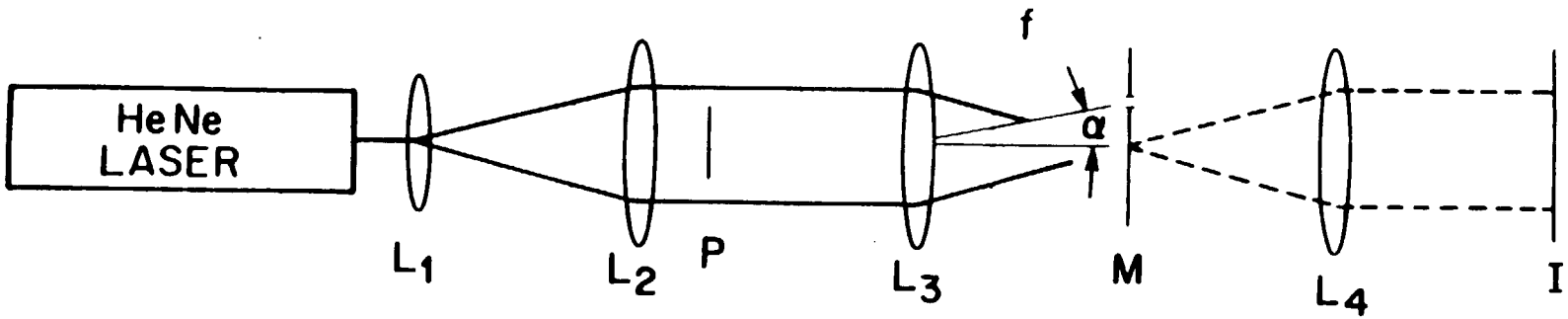


LASER SPECKLE VELOCIMETRY OPTICAL ANALYSIS

YOUNG'S FRINGE ANALYSIS

- DIFFRACTION HALO
- STRAIGHT, PARALLEL INTERFERENCE FRINGES TRANSVERSE TO FLOW
- $d = \lambda/\sin\alpha$, $v = d/t$
- POINT-BY-POINT PROCEDURE

FOURIER FILTERING ANALYSIS



L_1, L_2: BEAM EXPANDER

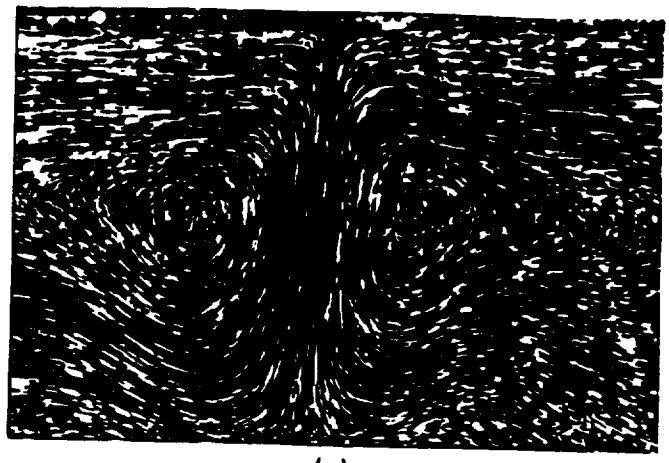
L_3, L_4: CONVERGING LENSES

P: SPECKLEGRAM

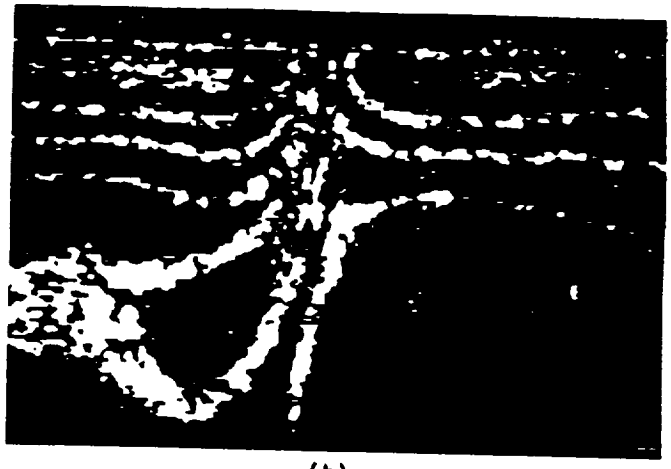
I: IMAGE PLANE

M: OPAQUE MASK WITH A CIRCULAR APERTURE

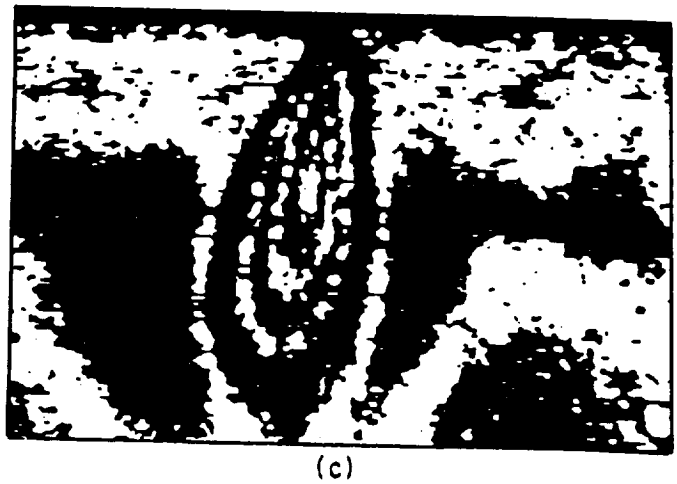
α: APERTURE OFFSET ANGLE



(a)



(b)



(c)

LASER SPECKLE VELOCIMETRY OPTICAL ANALYSIS

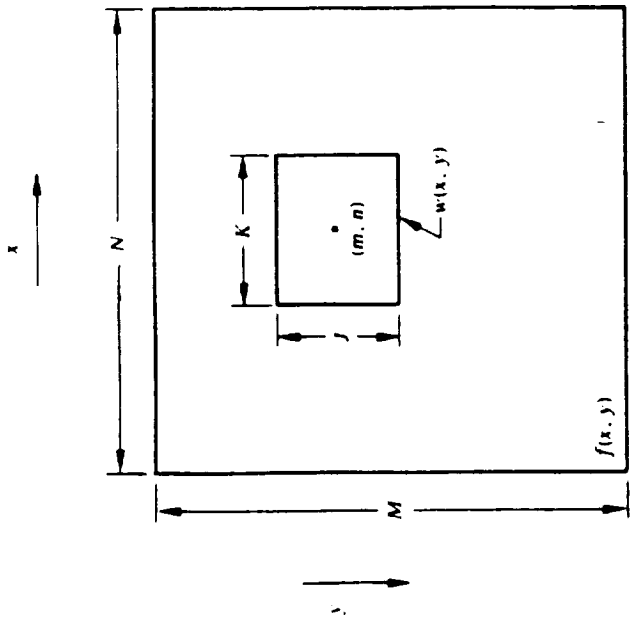
FOURIER FILTERING

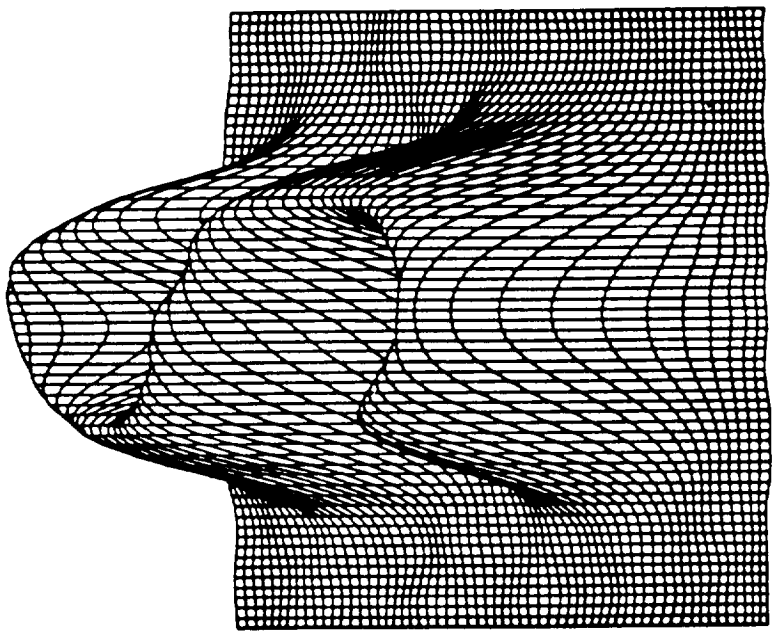
- OPTICAL FOURIER TRANSFORM
- VELOCITY COMPONENT FRINGES
- $d = \lambda/\sin\alpha$, $v = d/t$
- FULL-FIELD PROCEDURE

DIGITAL CORRELATION ANALYSIS

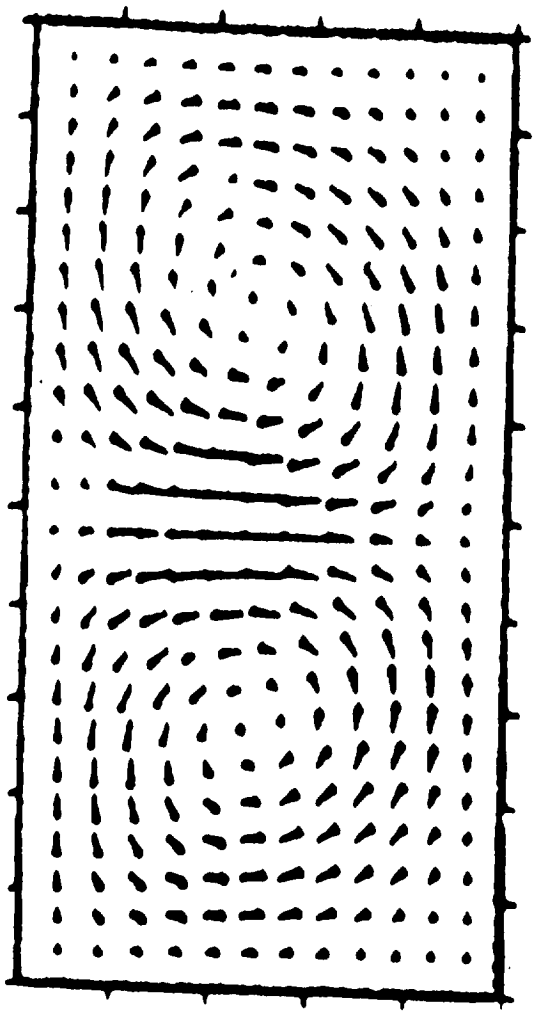
NASA

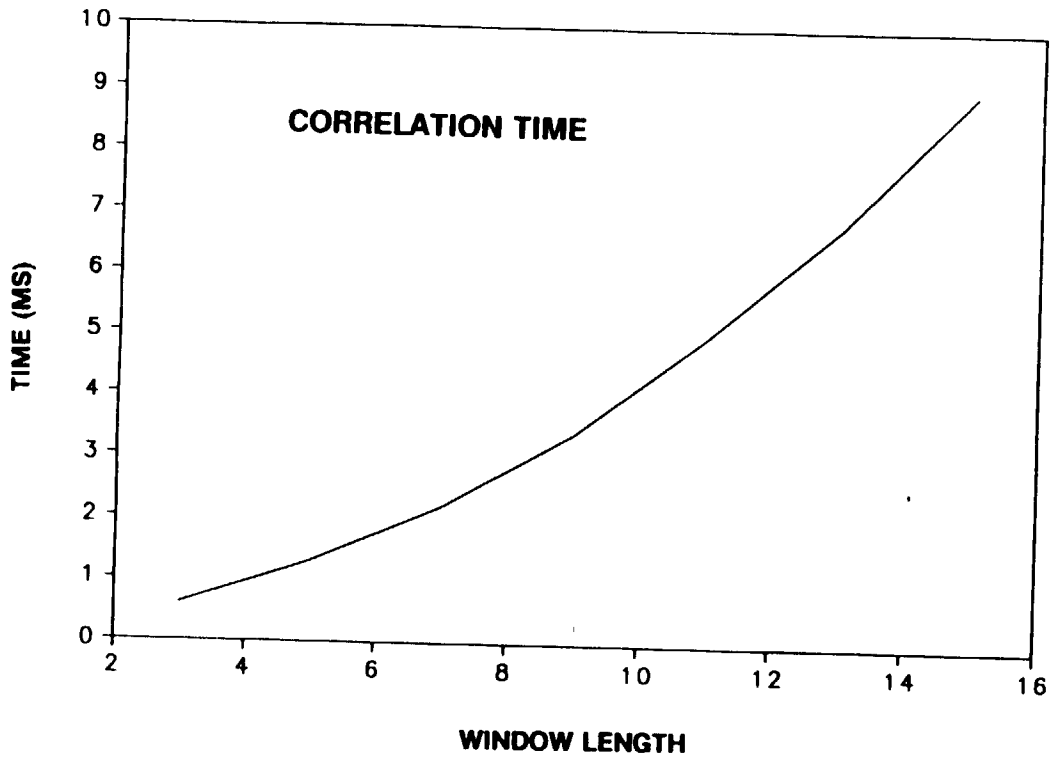
NASA





$$r(m, n) = \frac{\sum_x \sum_y [f(x, y) - \bar{f}(x, y)][w(x - m, y - n) - \bar{w}]}{\left[\sum_x \sum_y [f(x, y) - \bar{f}(x, y)]^2 \sum_x \sum_y [w(x - m, y - n) - \bar{w}]^2\right]^{1/2}}$$




CORRELATION TIME
TIME (MS)
WINDOW LENGTH
0
1
2
3
4
5
6
7
8
9
10
2
4
6
8
10
12
14
16

LASER SPECKLE VELOCIMETRY
DIGITAL ANALYSIS

CORRELATION METHOD OF ANALYSIS

- PATTERN MATCHING TECHNIQUE
- ELIMINATES NEED FOR SCANNING IMAGES
- MEASURES DISPLACEMENTS LARGER AND SMALLER THAN SPECKLE SIZE
- POINT-BY-POINT PROCEDURE

THE LSV TECHNIQUE
SUMMARY

- SEED
- SLICE
- RECORD
- ANALYZE

COMPARISON OF TECHNIQUES FOR PARTICLE IMAGING

YOUNG'S FRINGE ANALYSIS

- POINT-BY-POINT INTERROGATION FOR VELOCITY VECTOR BY SCANNING SPECKLEGRAM
- SIGN AMBIGUITY IN DETERMINING DIRECTION OF VELOCITY VECTOR
- DISPLACEMENT RANGE DEPENDENT ON SPECKLE SIZE
- FRINGE CONTRAST IN HALO INFLUENCED BY SECONDARY SPECKLE

FOURIER FILTERING ANALYSIS

- FULL-FIELD MAP OF A SINGLE VELOCITY COMPONENT BY SCANNING THE TRANSFORM PLANE
- SIGN AMBIGUITY IN DETERMINING DIRECTION OF VELOCITY COMPONENT
- DISPLACEMENT RANGE DEPENDENT ON SPECKLE SIZE
- POOR CONTRAST FRINGES IN FILTERED IMAGE

DIGITAL CORRELATION ANALYSIS

- POINT-BY-POINT INTERROGATION FOR VELOCITY VECTOR BY ELECTRONIC SCANNING
- DIRECTION OF THE VELOCITY VECTOR UNIQUELY DETERMINED
- DISPLACEMENT RANGE LIMITED BY SENSOR RESOLUTION AND CAMEARA MAGNIFICATION
- DIGITAL OUTPUT COMPATIBLE WITH TELECOMMUNICATION LINKS

FLUID FLOW MEASUREMENT

BY

DIGITAL CORRELATION

JOHN GILBERT
UNIV. OF ALABAMA IN HUNTSVILLE
HUNTSVILLE, AL 35899

DONALD MATTHYS
MARQUETTE UNIVERSITY
MILWAUKEE, WI 53233

OVERALL OBJECTIVE

PRODUCE A PHYSICAL SYSTEM SUITABLE FOR A SPACE ENVIRONMENT THAT CAN MEASURE FLUID VELOCITIES IN A 3-D VOLUME BY THE DEVELOPMENT OF A PARTICLE CORRELATION VELOCIMETRY TECHNIQUE

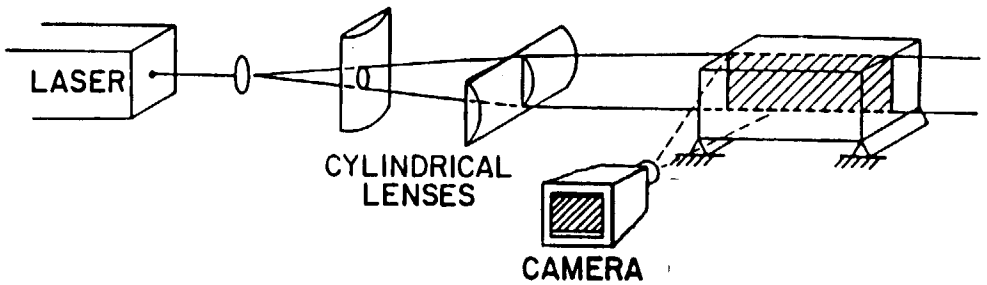
OBJECTIVE FOR FIRST YEAR

CONDUCT EXPERIMENTAL STUDIES ON A FLUID TEST CELL TO DEMONSTRATE THE SUITABILITY AND ACCURACY OF DIGITAL CORRELATION TECHNIQUES FOR MEASURING 2-D FLUID FLOW

TASKS FOR FIRST YEAR

- ASSEMBLE AND TEST COMPUTER HARDWARE AND SOFTWARE
- DESIGN AN APPROPRIATE ILLUMINATION AND DETECTION SYSTEM FOR MAKING VELOCITY MEASUREMENTS WITHIN A TEST CELL
- DESIGN AND CONSTRUCT A TEST CELL
- MAKE PRELIMINARY EVALUATIONS ON FLUID AND SEEDING REQUIREMENTS
- PERFORM CONTROLLED TESTS

SCATTERED LIGHT
LASER SPECKLE METROLOGY



HARDWARE

- LASER
- OPTICS
- CELL
- CAMERA (DIGITAL, FILM)
- COMPUTER

SOFTWARE

- IMAGE ACQUISITION
- CORRELATION
- GRAPHICS

FLUID FLOW MEASUREMENT

BY

DIGITAL CORRELATION

JOHN GILBERT
UNIV. OF ALABAMA IN HUNTSVILLE
HUNTSVILLE, AL 35899

DONALD MATTHYS
MARQUETTE UNIVERSITY
MILWAUKEE, WI 53233

CORRELATION STUDIES

- SIMULATED DATA PAIRS
- REAL DATA PAIRS

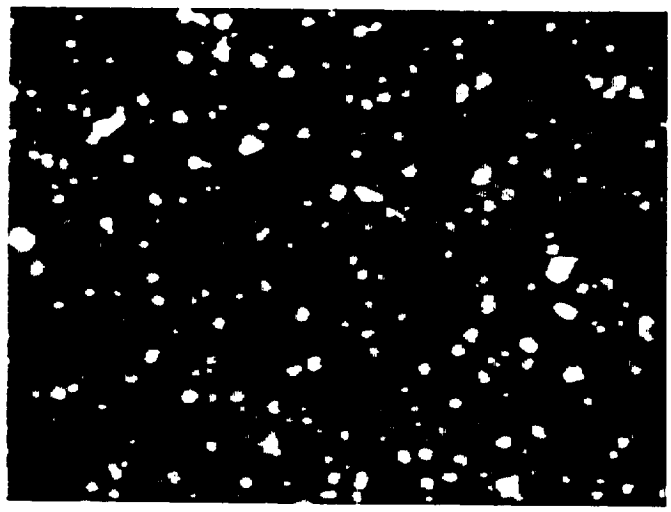
SIMULATED DATA PAIRS

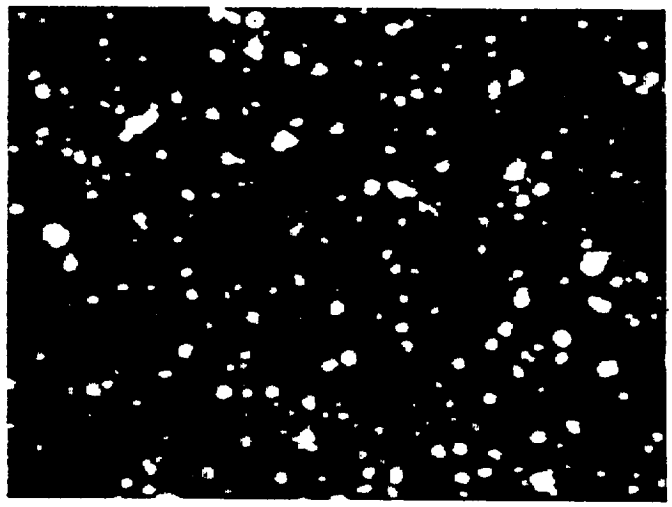
- SINGLE RECORDING
- PERIODIC RECORDING
- APERIODIC RECORDING

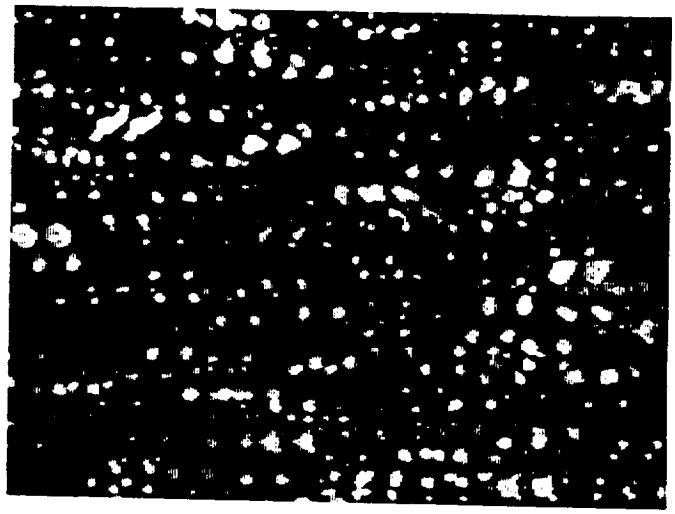
SINGLE RECORDING

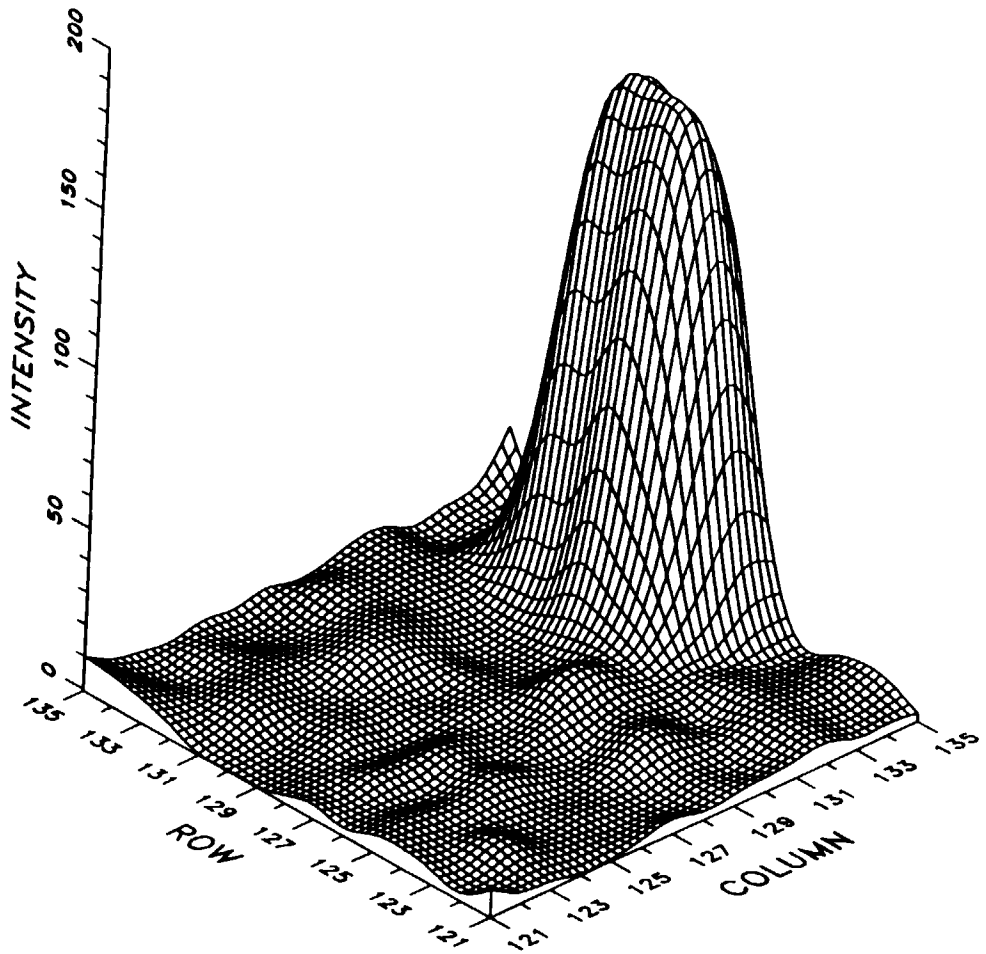
DATA SETS

- SPECKLE PATTERNS
- WINDOW AT (128,128) AND CORRELATION VALUES
- WINDOW AT (75,184) AND CORRELATION VALUES

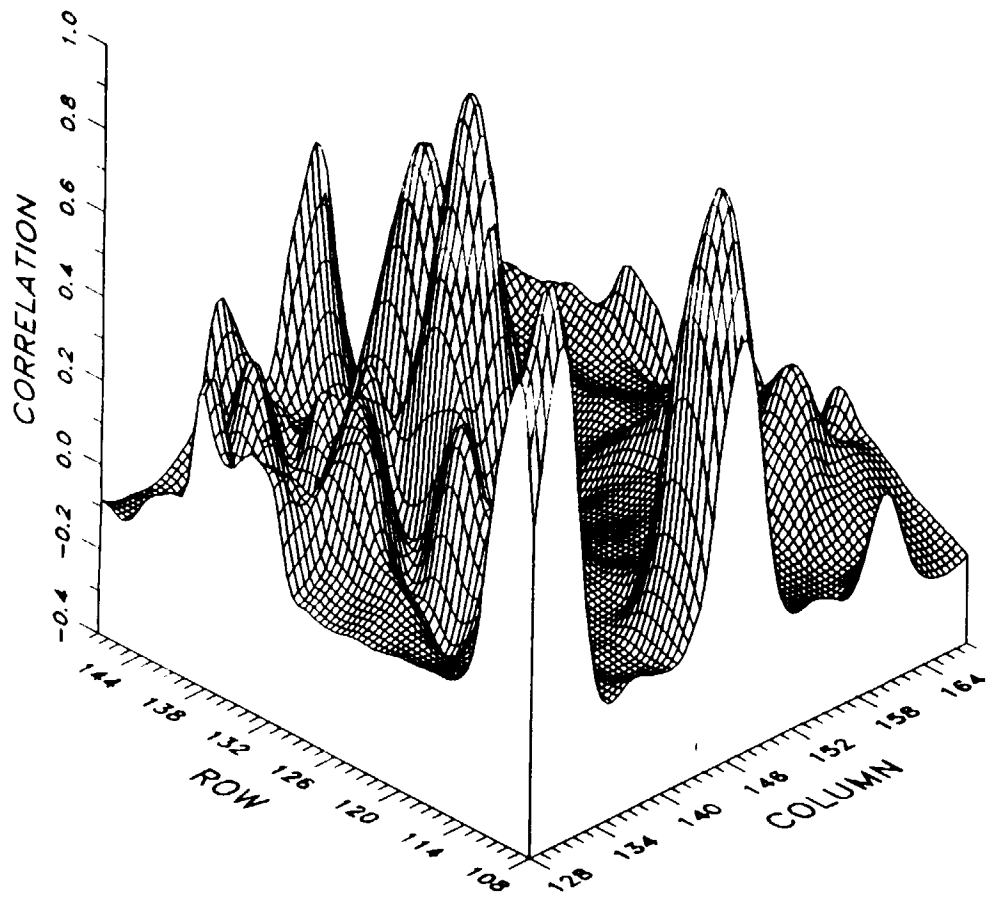




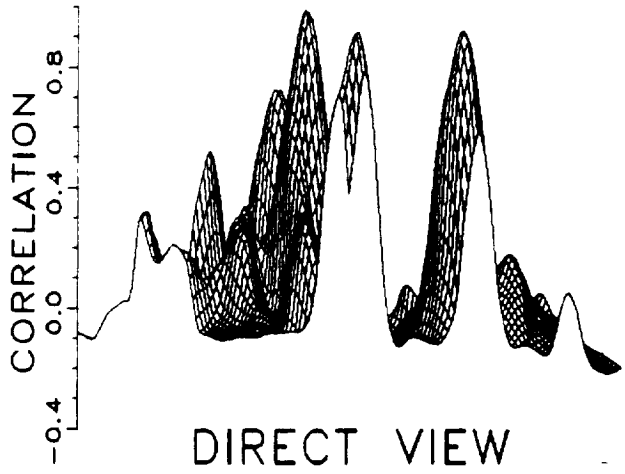




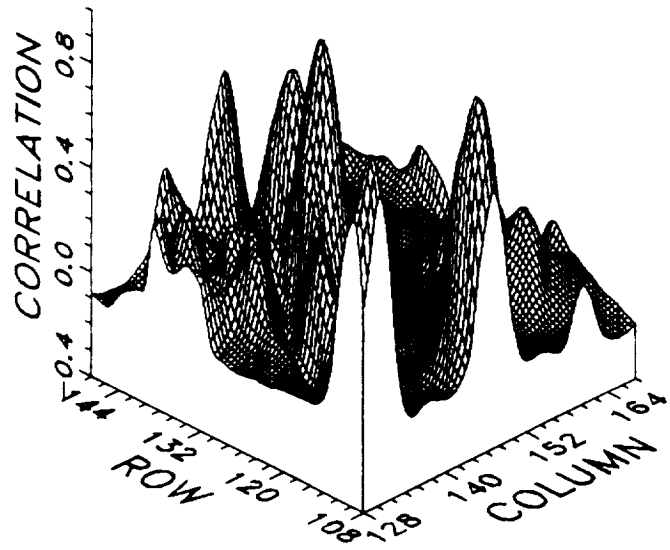
CORRELATION WINDOW



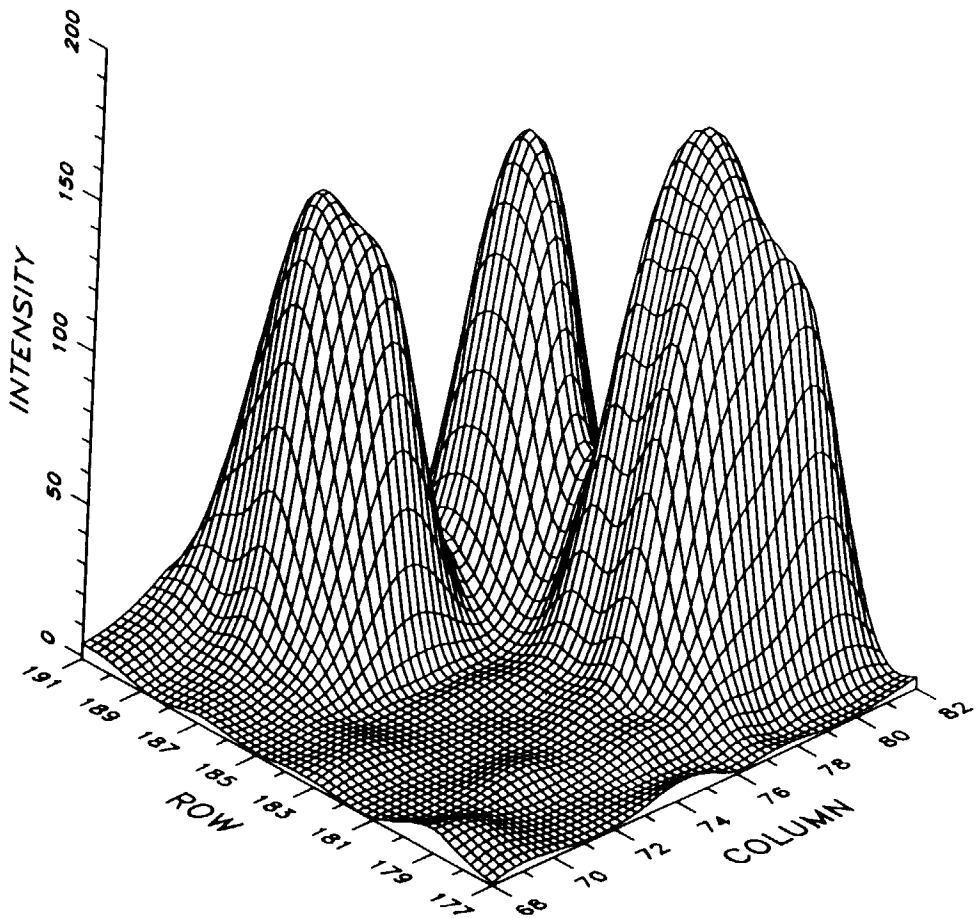
SEARCH REGION



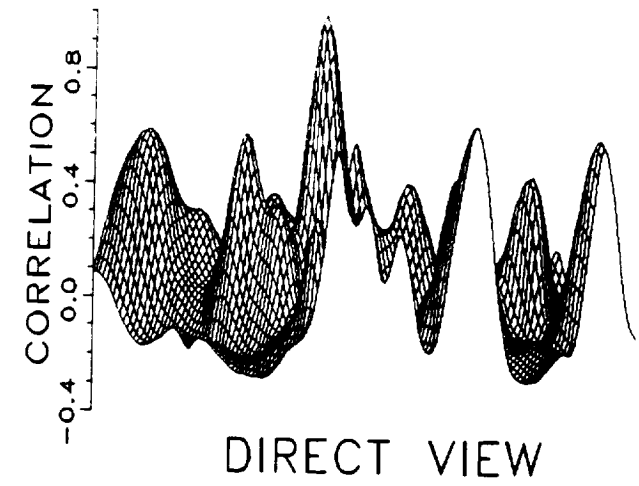
DIRECT VIEW



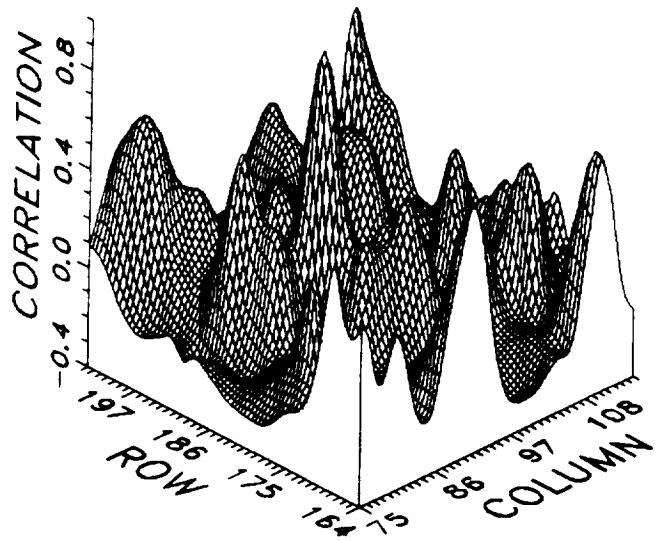
SEARCH REGION



CORRELATION WINDOW



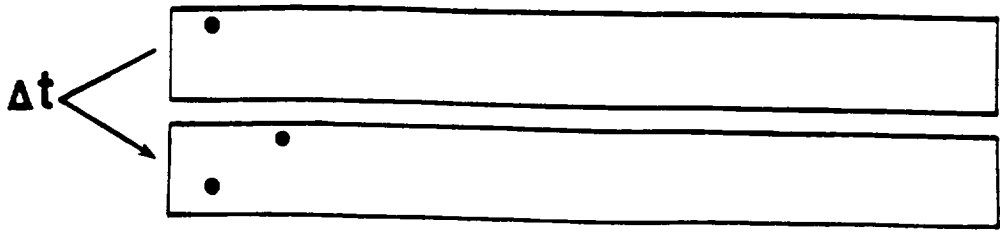
DIRECT VIEW



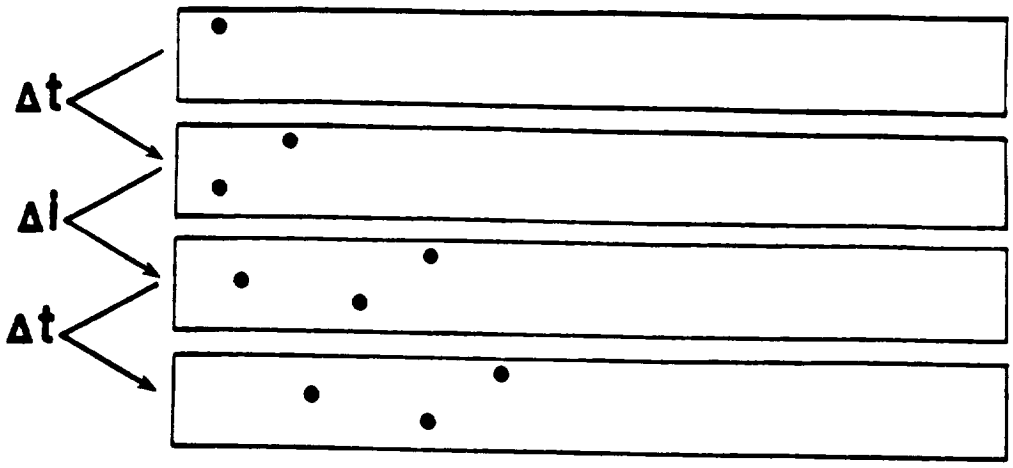
SEARCH REGION

PERIODIC RECORDING

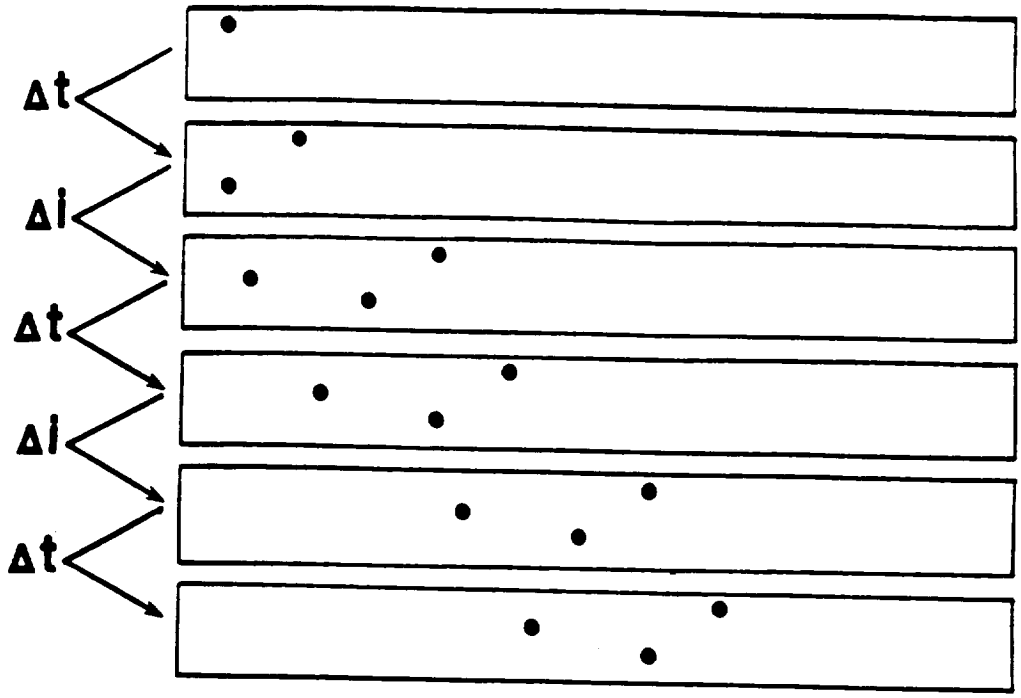
SPECKLE IMAGES
RECORDED AT PERIODIC INTERVALS



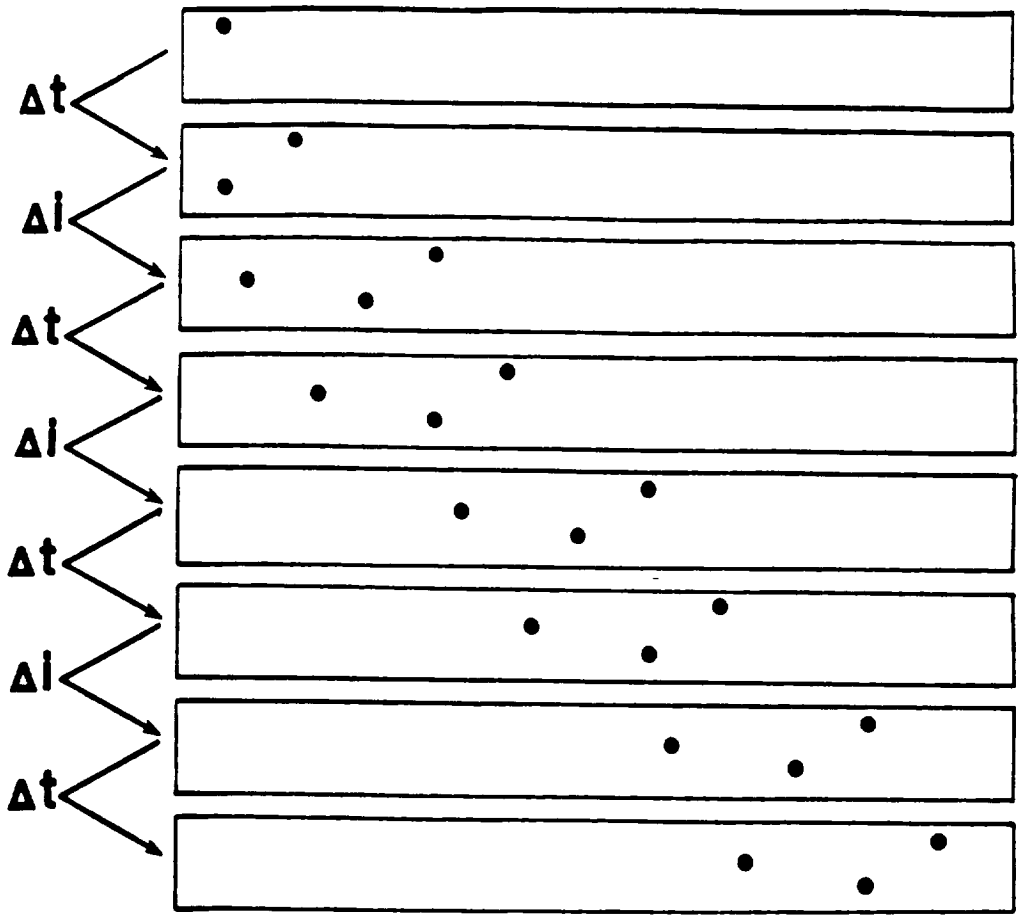
SPECKLE IMAGES
RECORDED AT PERIODIC INTERVALS



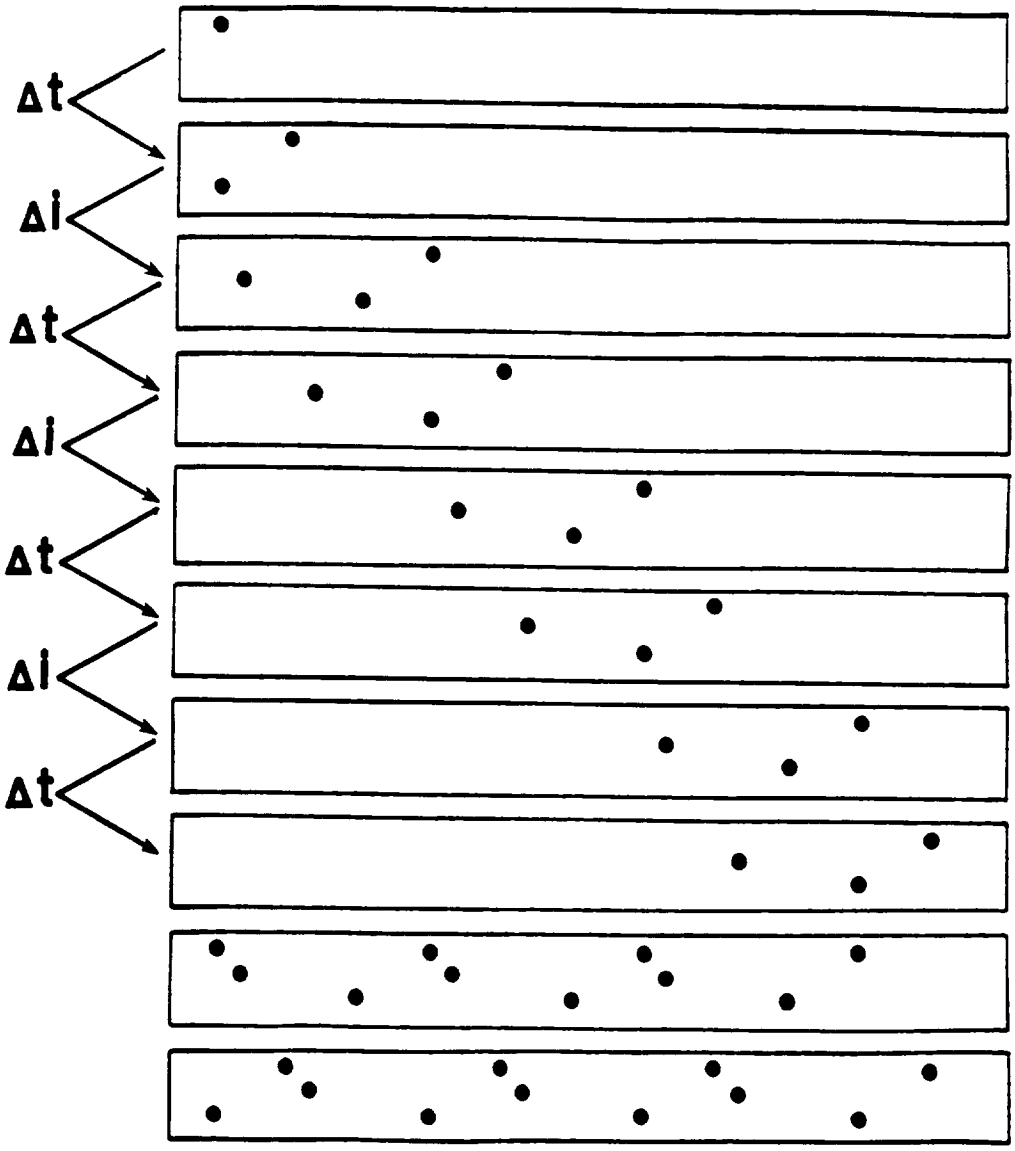
SPECKLE IMAGES
RECORDED AT PERIODIC INTERVALS



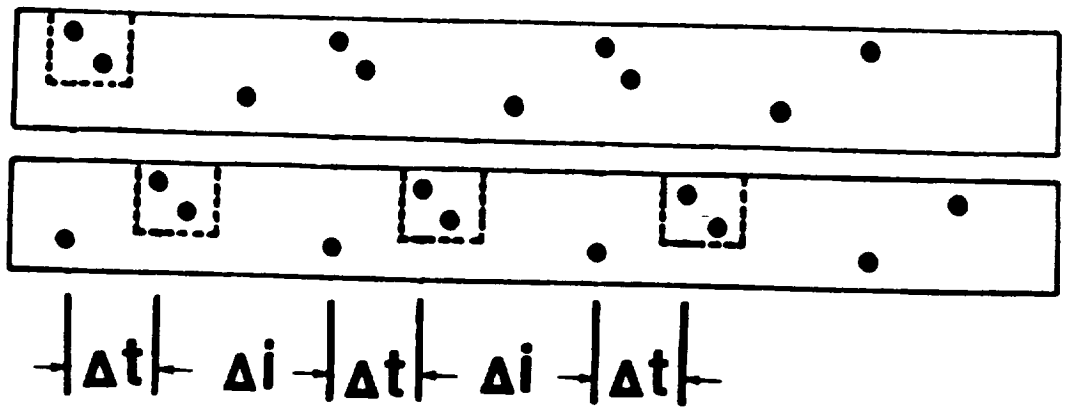
SPECKLE IMAGES
RECORDED AT PERIODIC INTERVALS

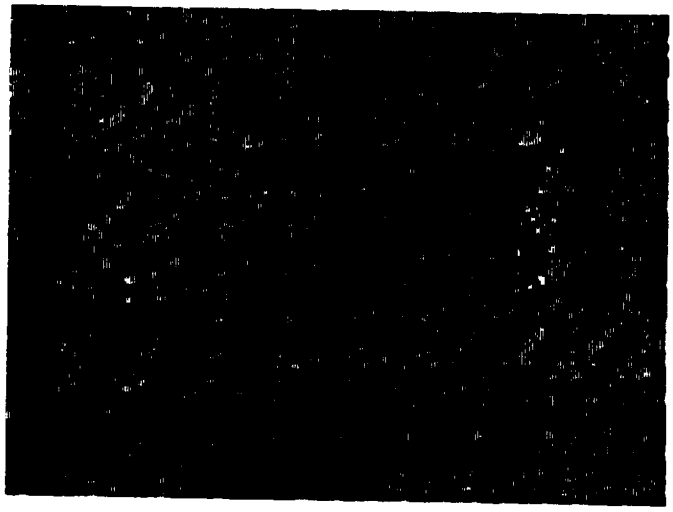


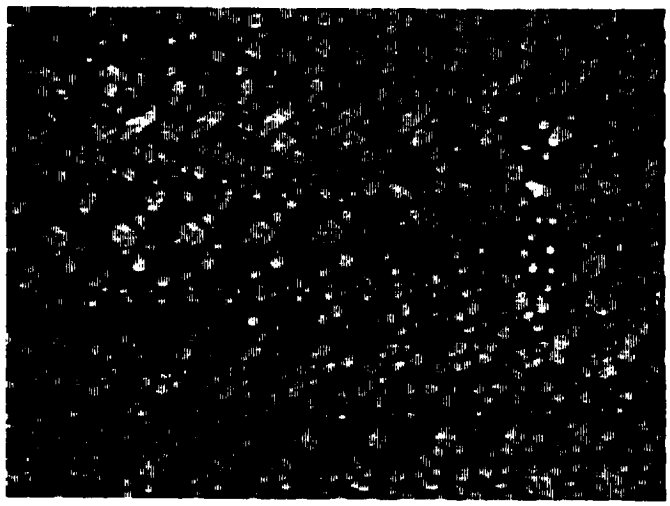
SPECKLE IMAGES
RECORDED AT PERIODIC INTERVALS

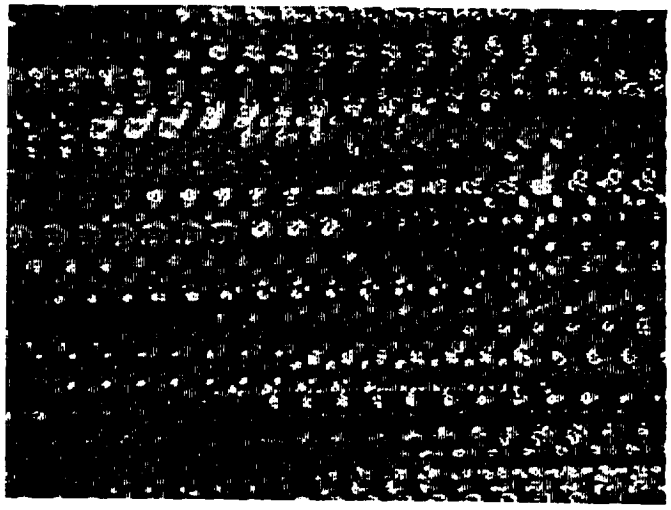


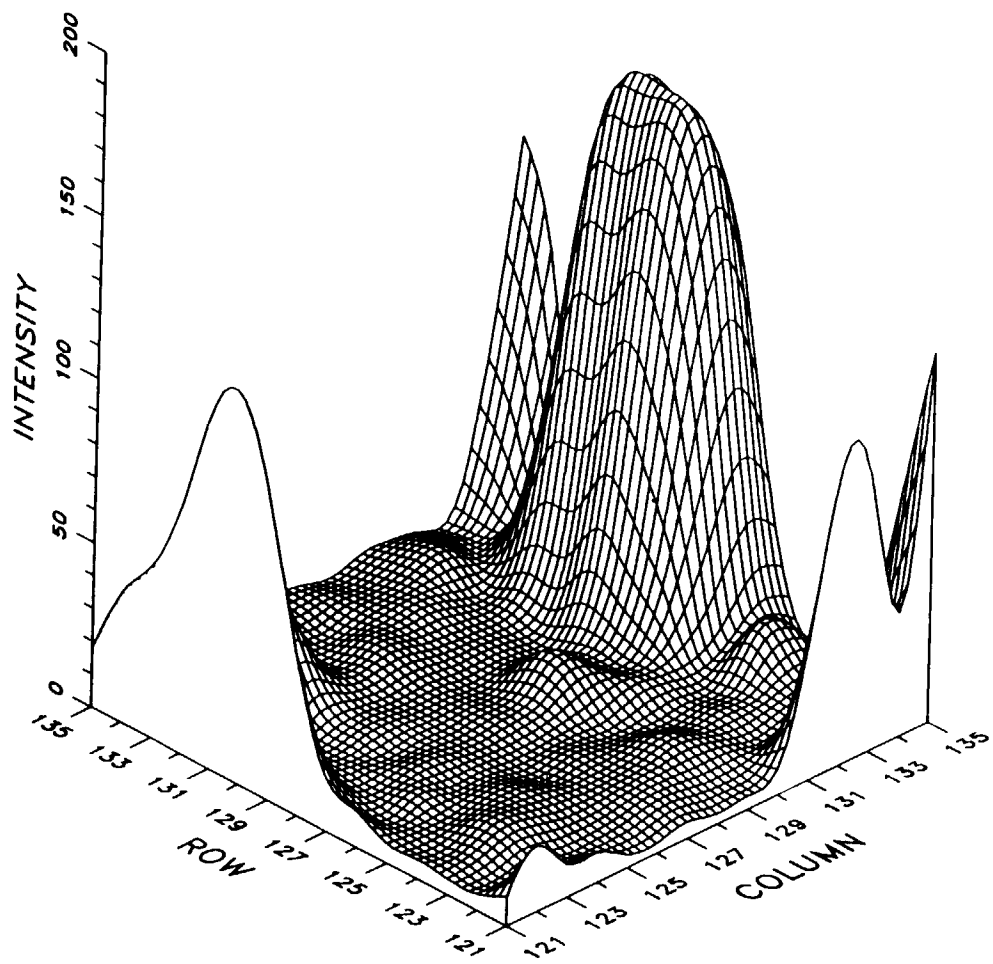
CORRELATION OF SPECKLE IMAGES RECORDED AT PERIODIC INTERVALS



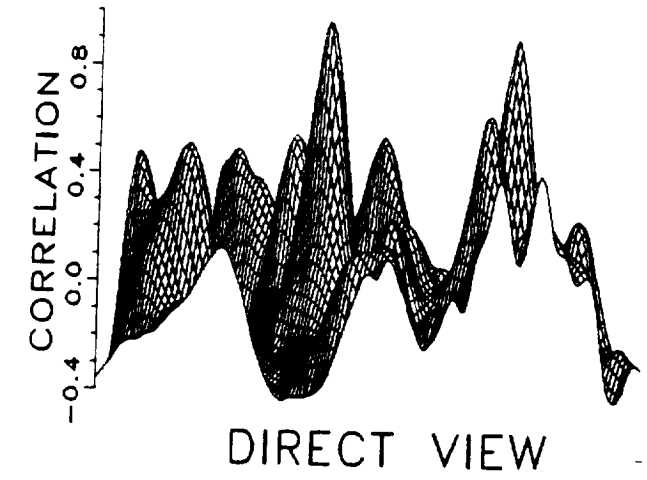




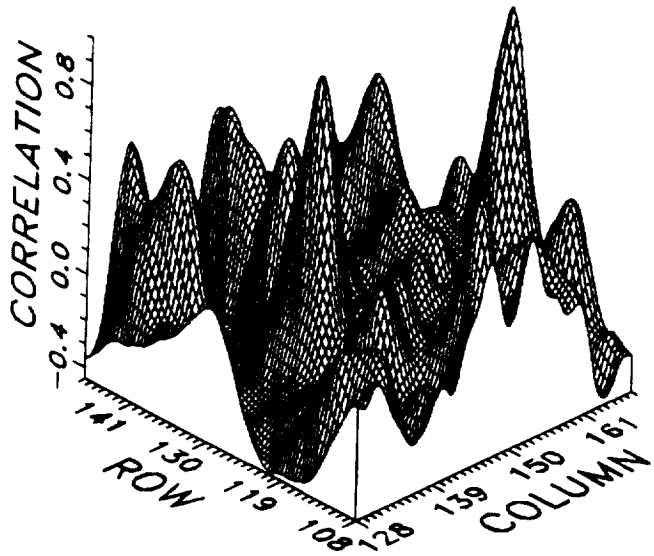




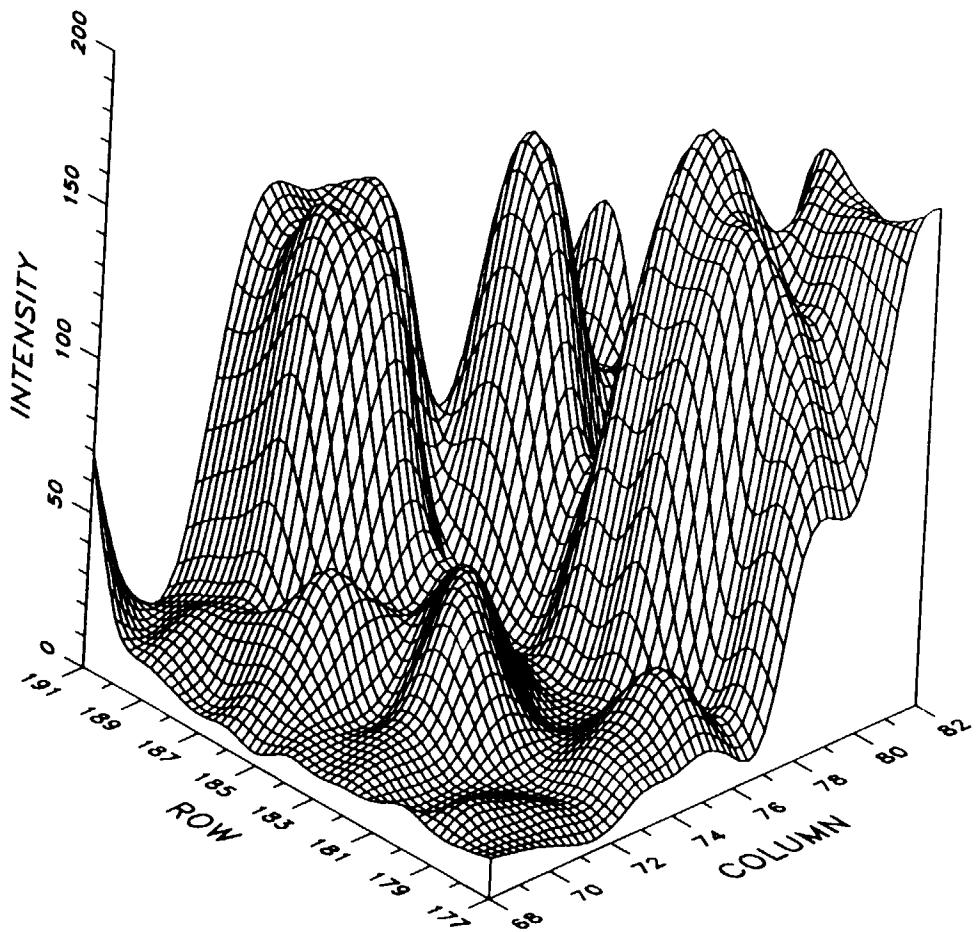
CORRELATION WINDOW



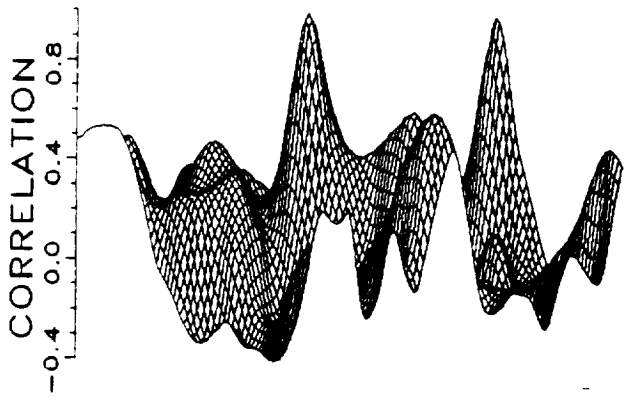
DIRECT VIEW



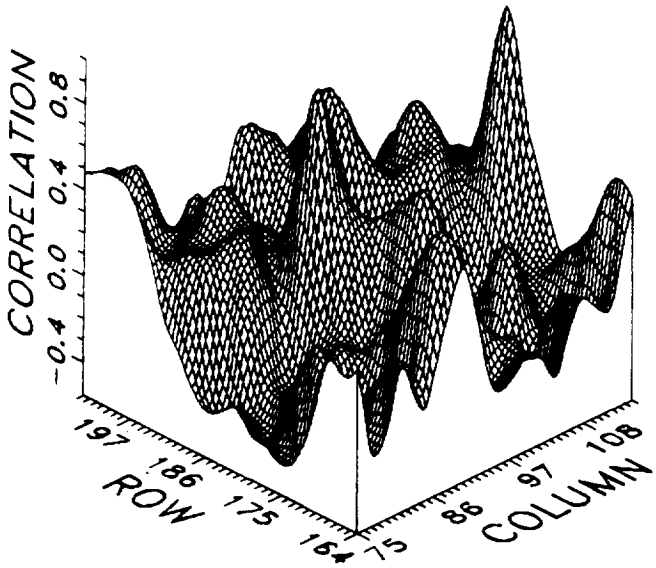
SEARCH REGION



CORRELATION WINDOW



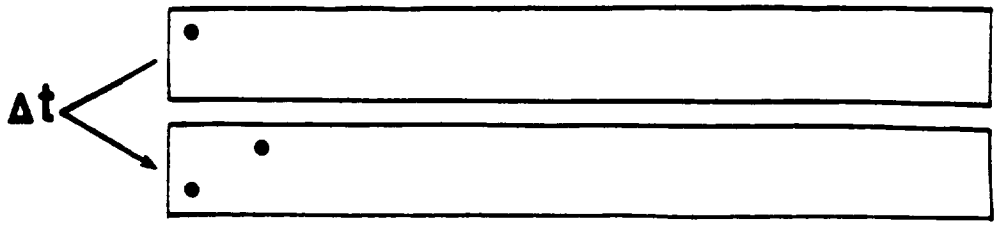
DIRECT VIEW



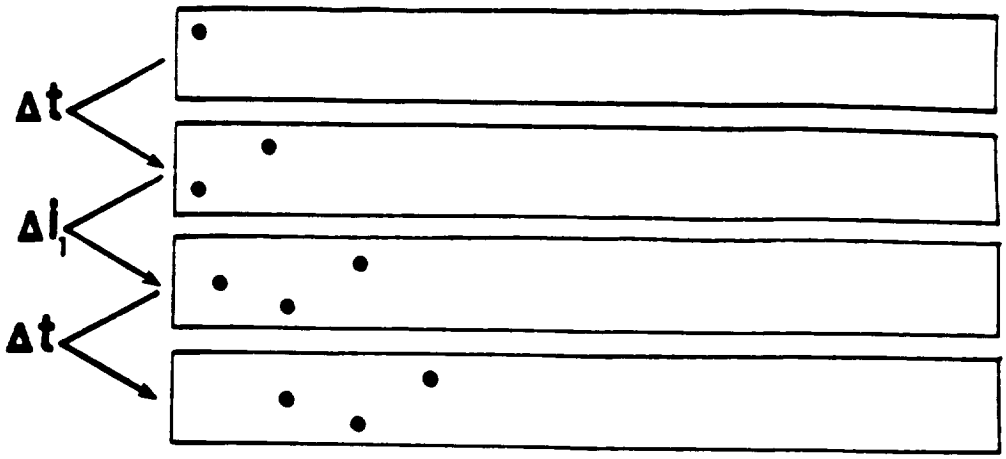
SEARCH REGION

APERIODIC RECORDING

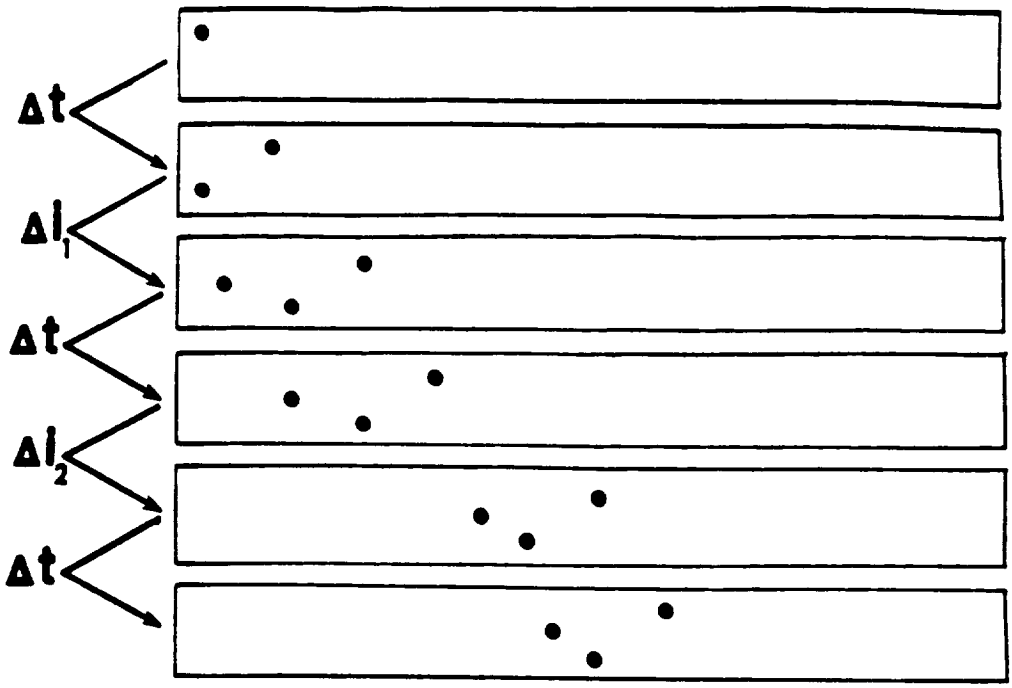
SPECKLE IMAGES
RECORDED AT RANDOM INTERVALS



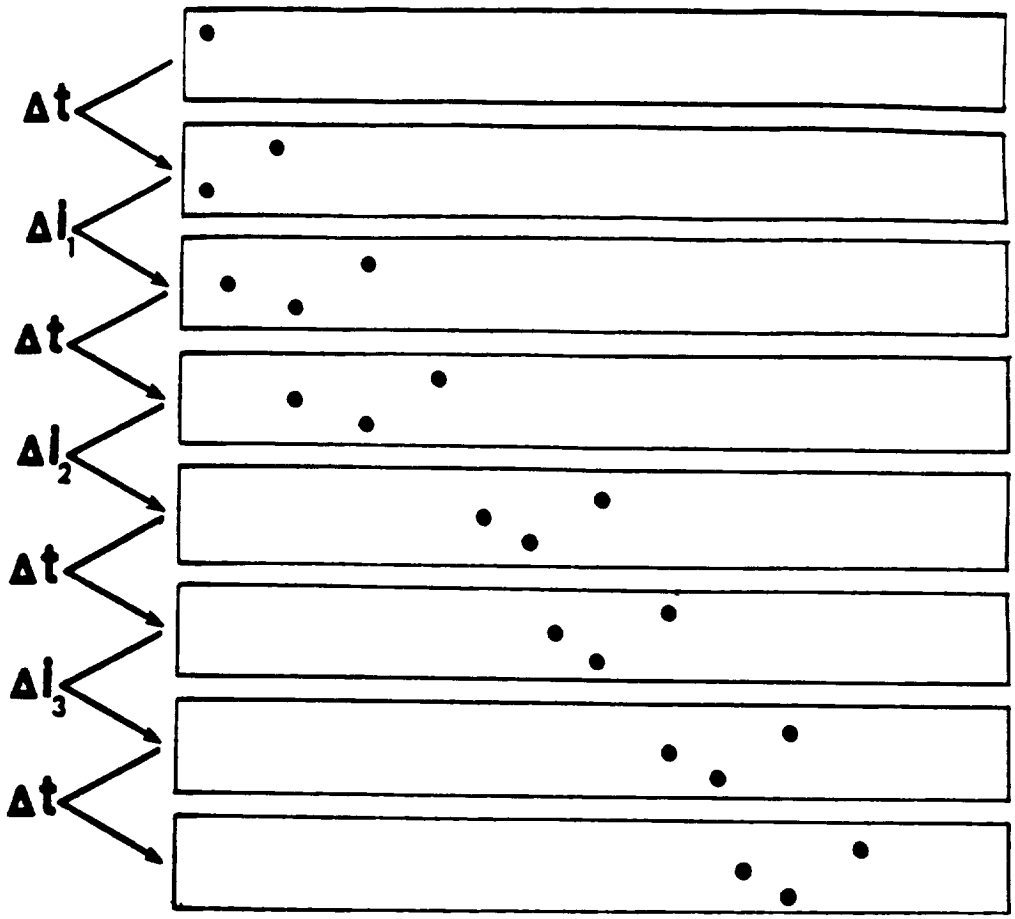
SPECKLE IMAGES
RECORDED AT RANDOM INTERVALS



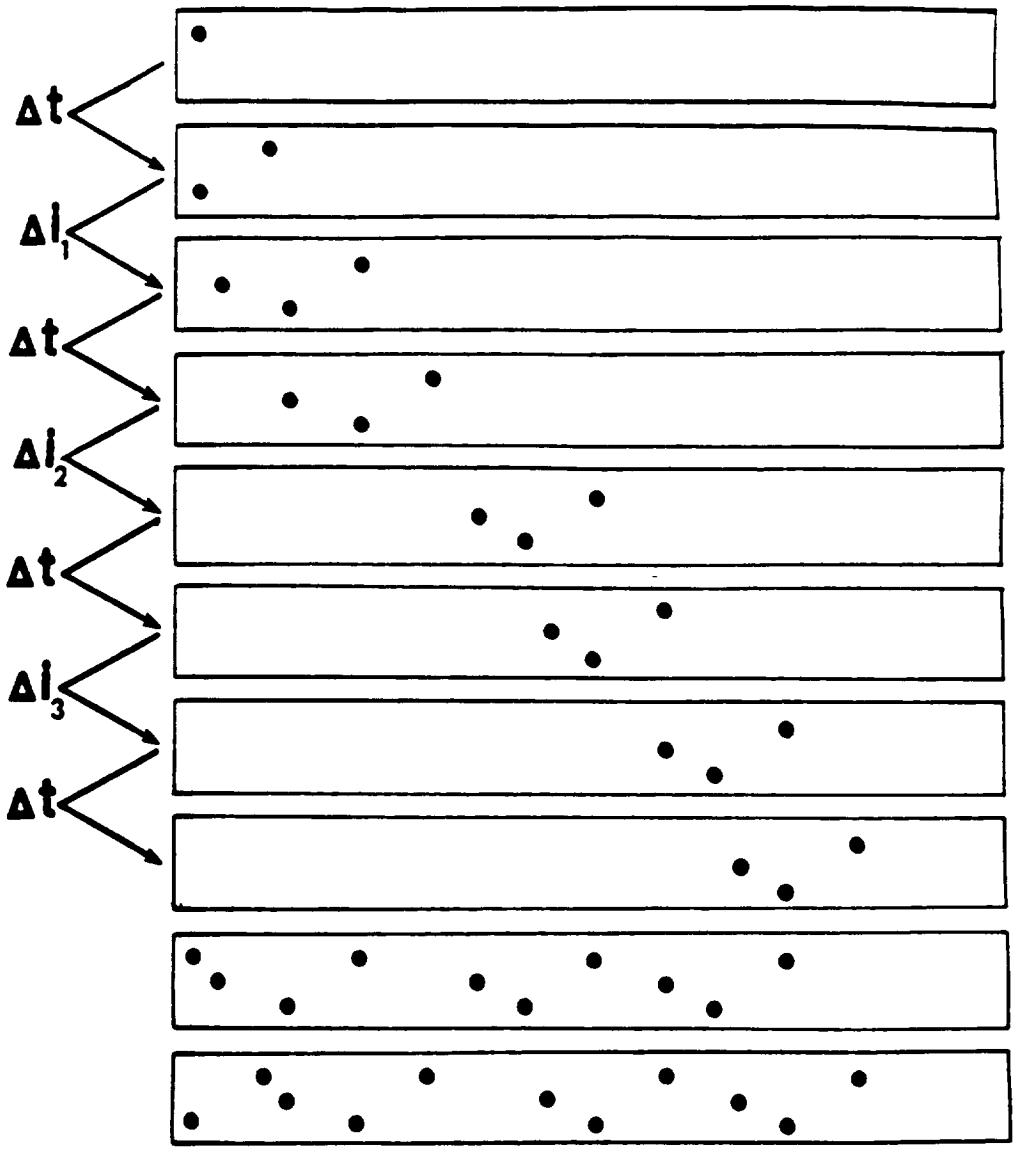
SPECKLE IMAGES
RECORDED AT RANDOM INTERVALS



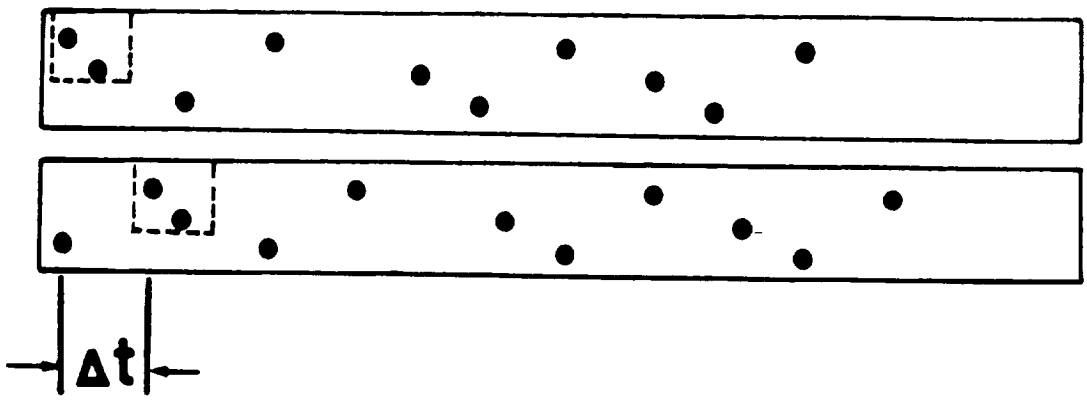
SPECKLE IMAGES
RECORDED AT RANDOM INTERVALS

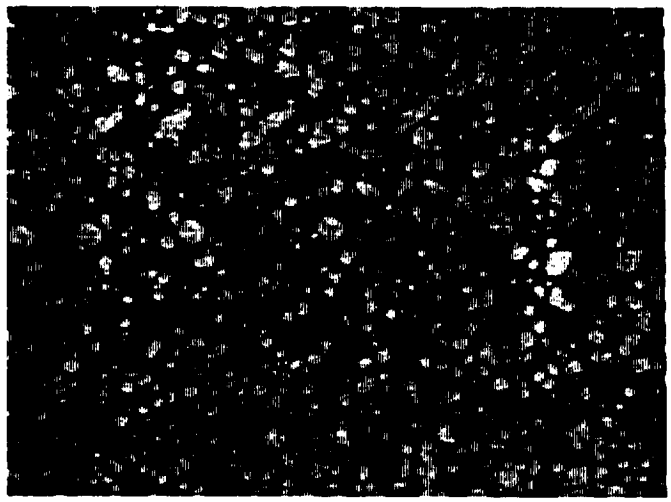


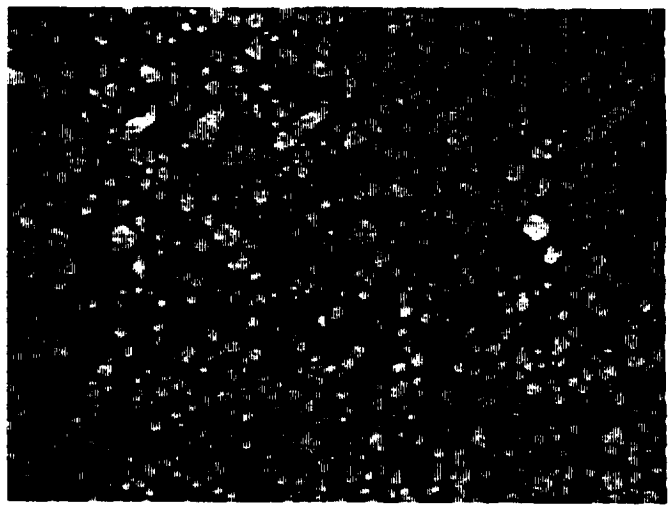
SPECKLE IMAGES
RECORDED AT RANDOM INTERVALS

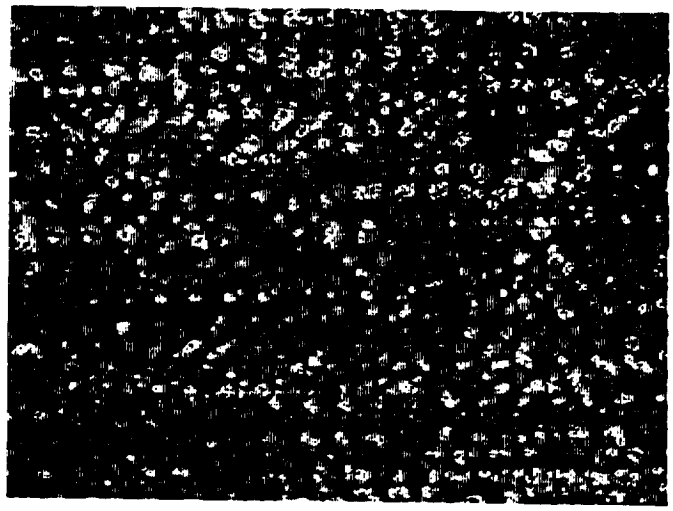


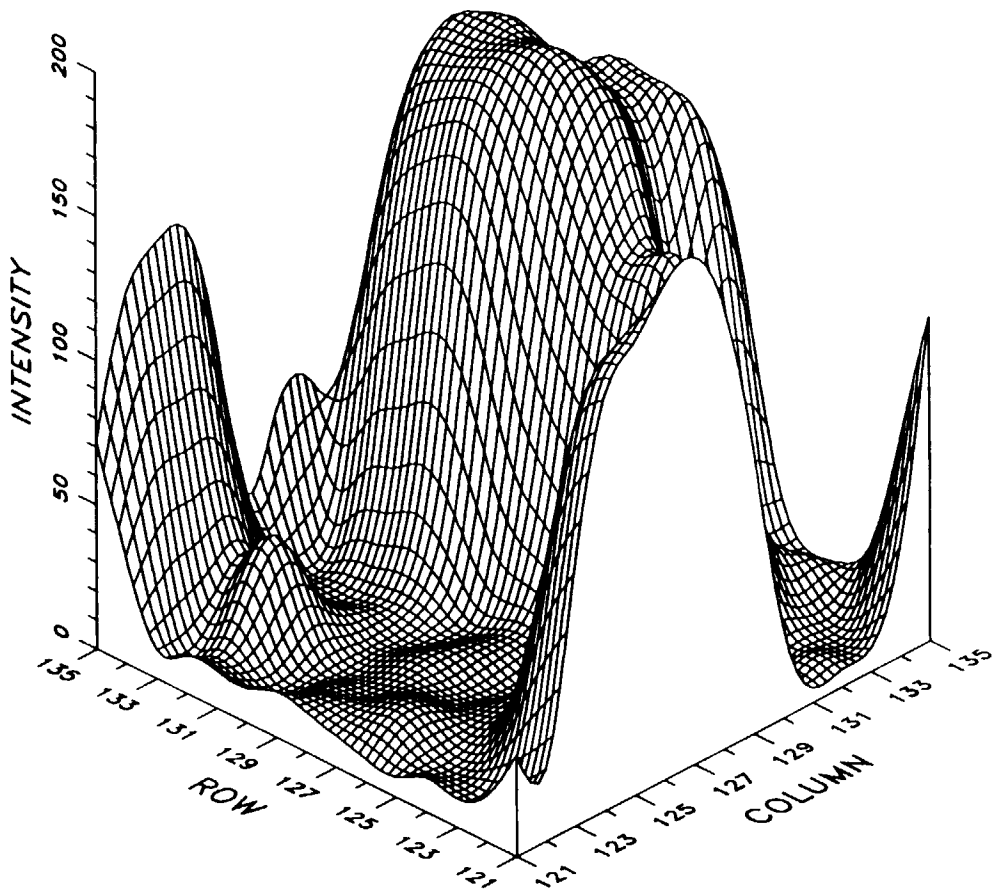
CORRELATION OF SPECKLE IMAGES RECORDED AT RANDOM INTERVALS



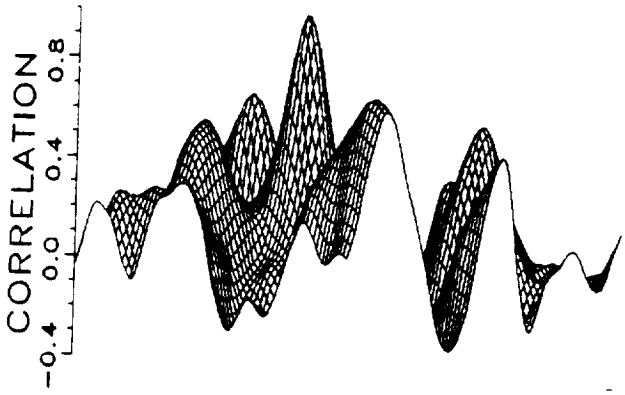




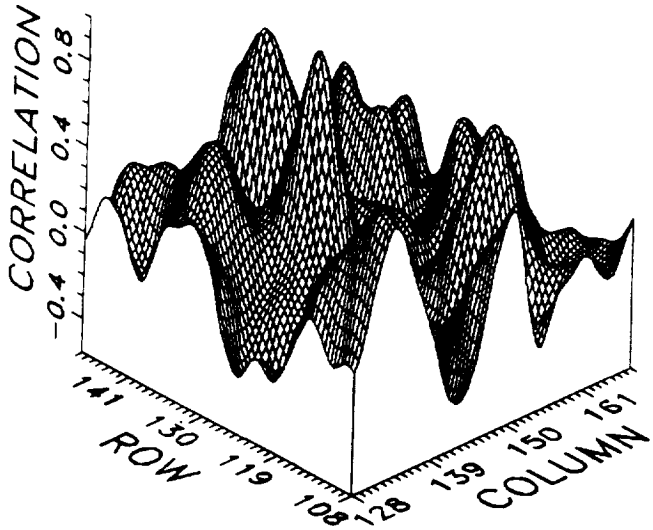




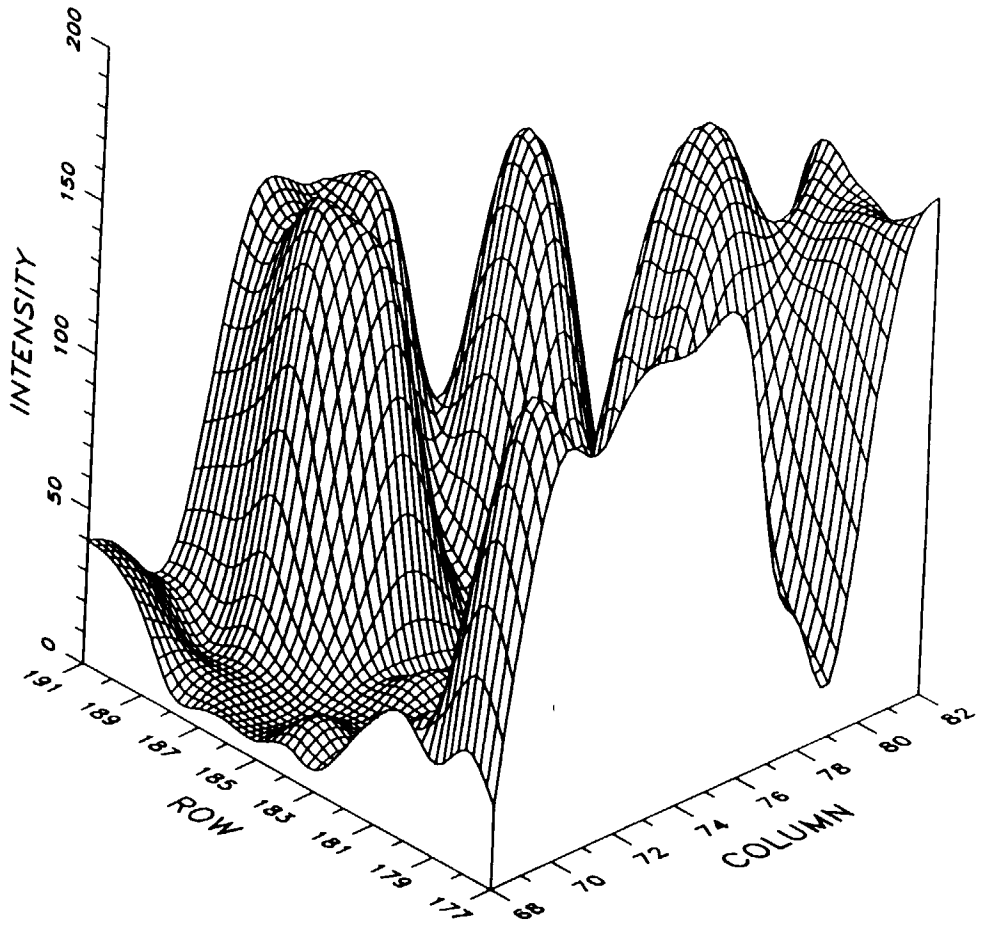
CORRELATION WINDOW



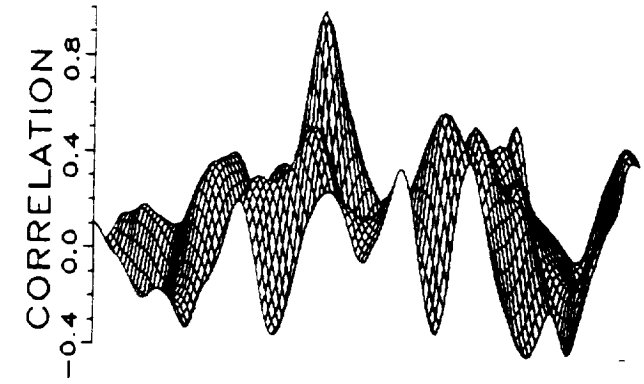
DIRECT VIEW



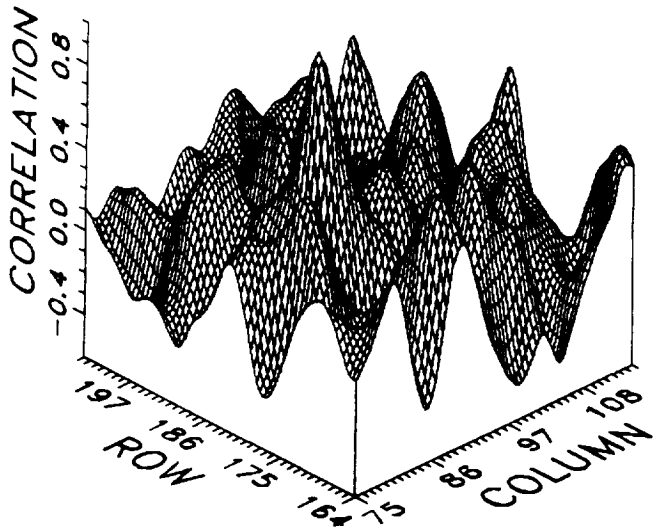
SEARCH REGION



CORRELATION WINDOW



DIRECT VIEW

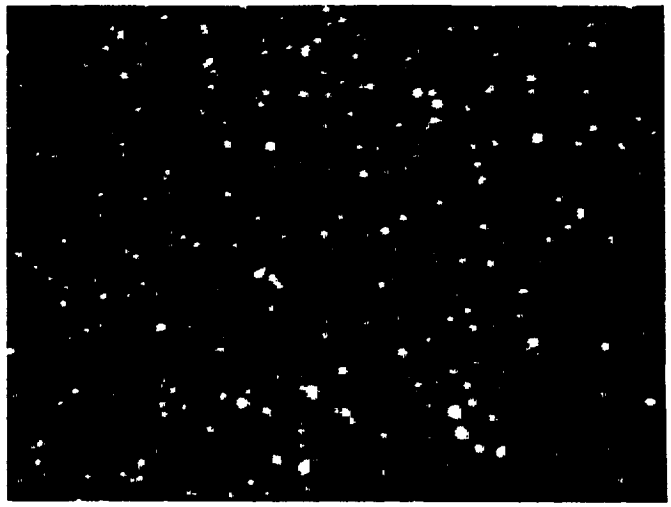


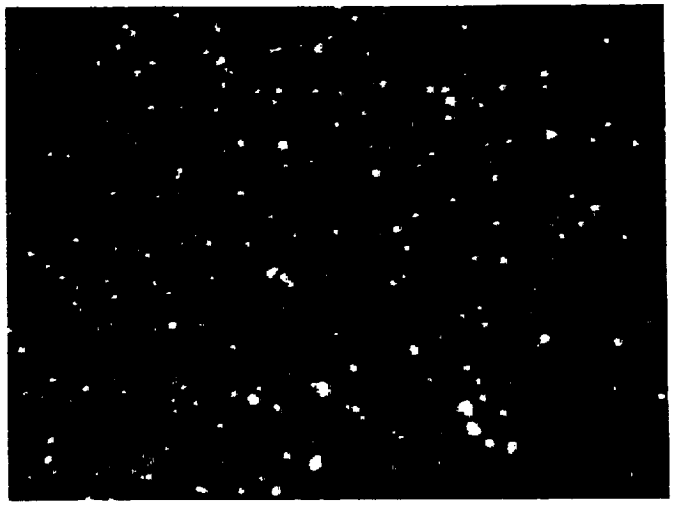
SEARCH REGION

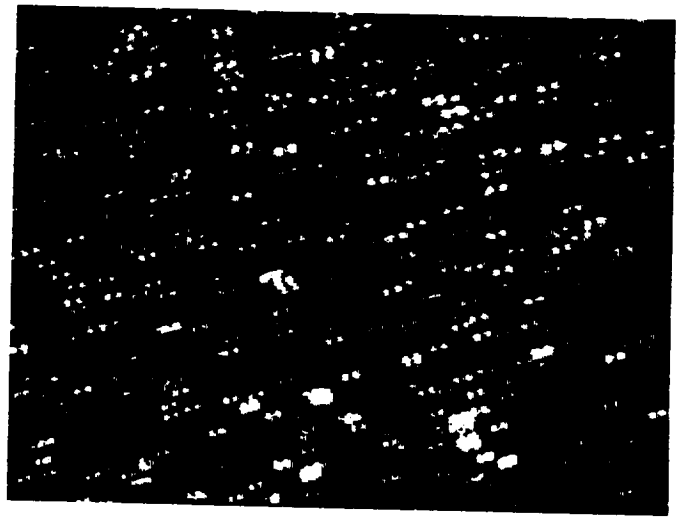
REAL DATA PAIRS

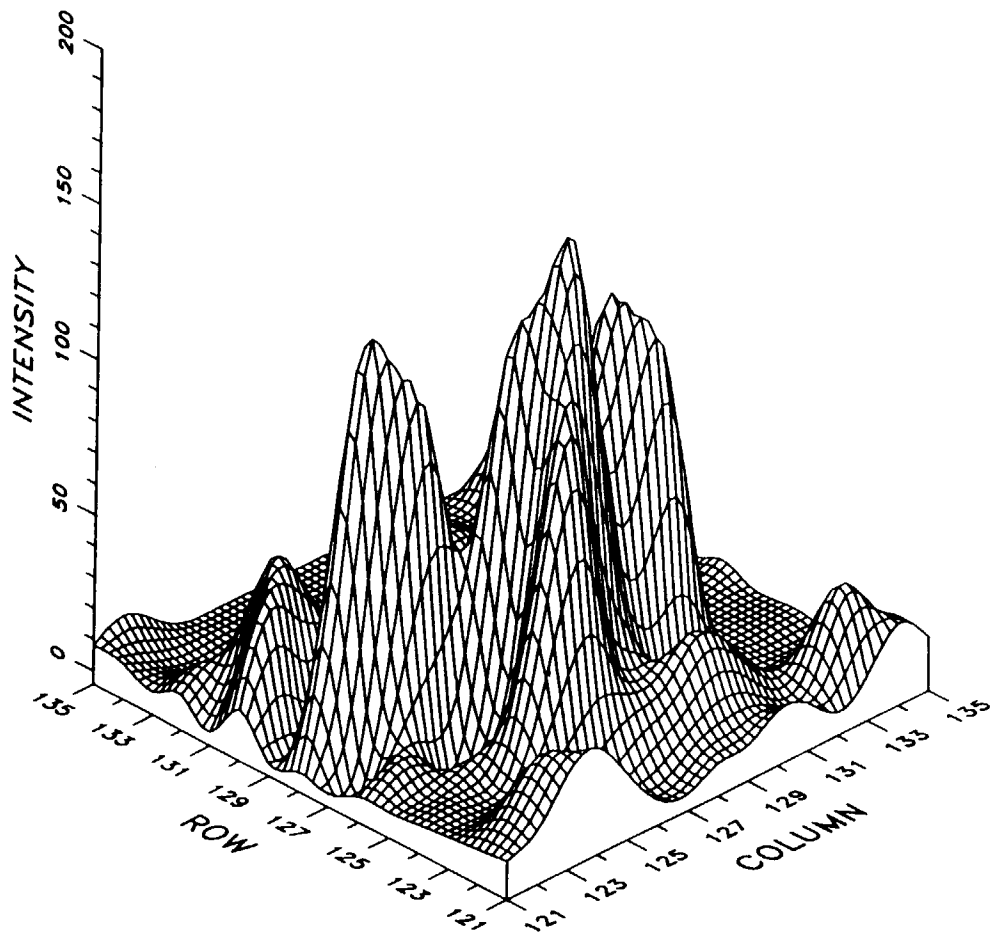
- SINGLE RECORDING
- APERIODIC RECORDING

SINGLE RECORDING

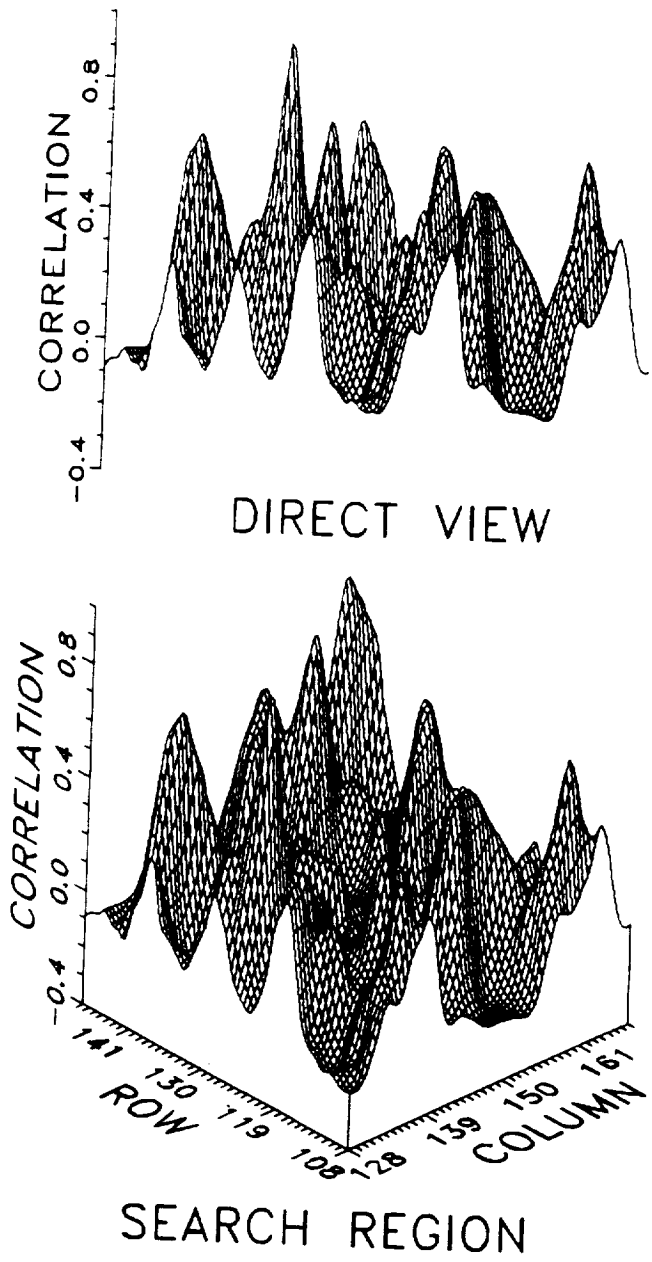


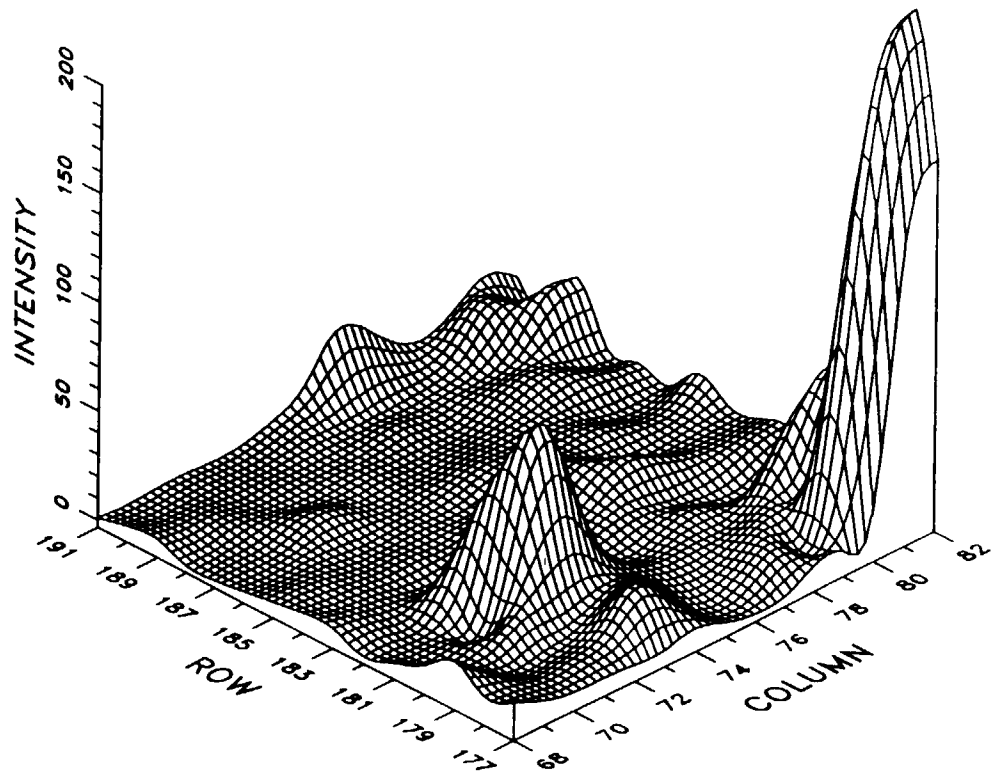




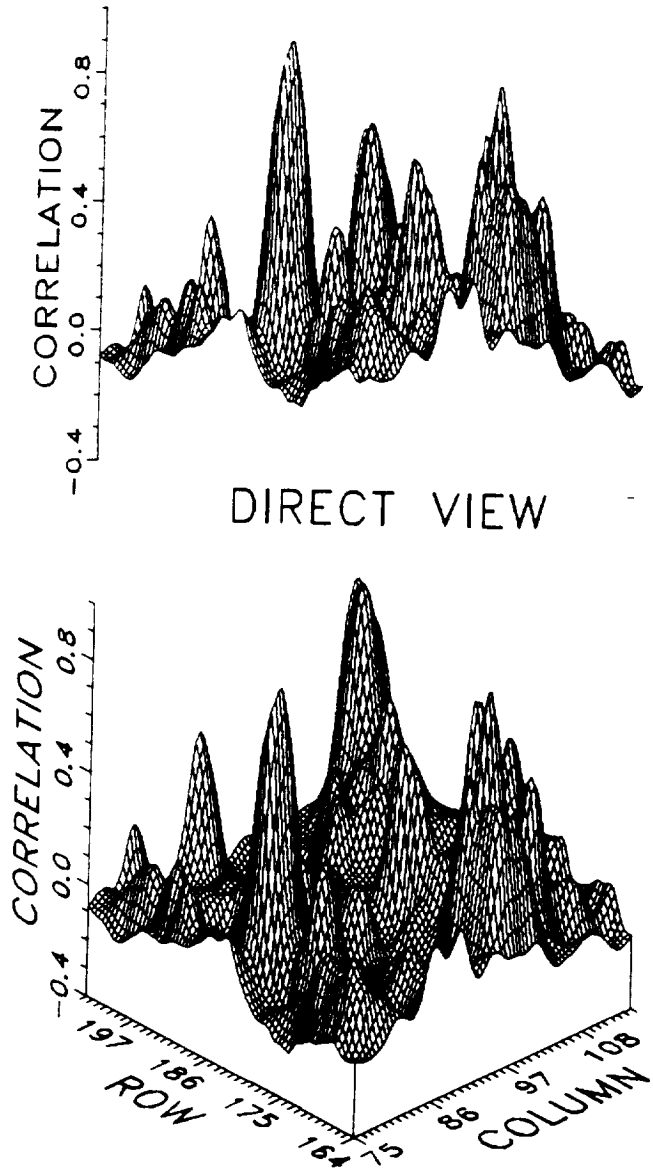


CORRELATION WINDOW

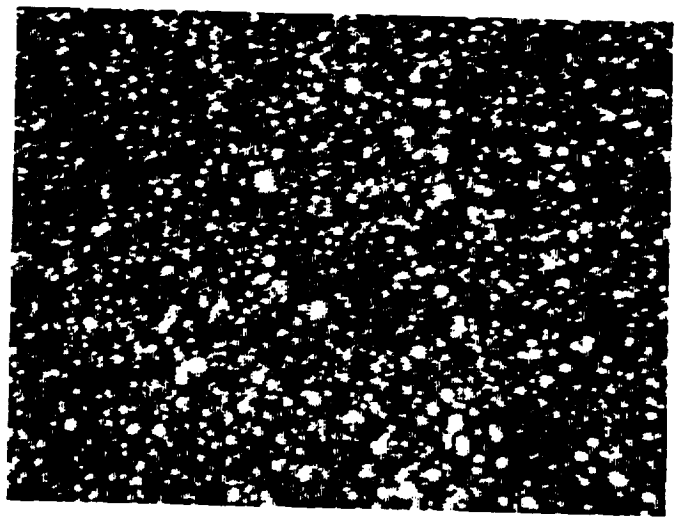

CORRELATION
0.8
0.4
0.0
-0.4
DIRECT VIEW
CORRELATION
0.8
0.4
0.0
-0.4
141
130
119
108
ROW
128
139
150
161
COLUMN
SEARCH REGION

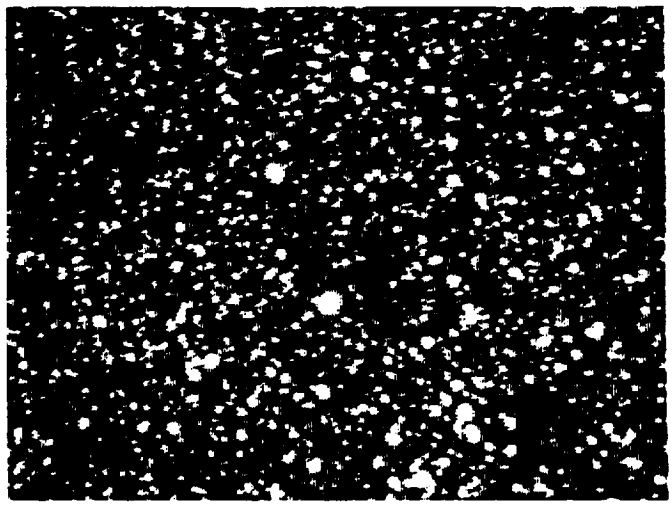


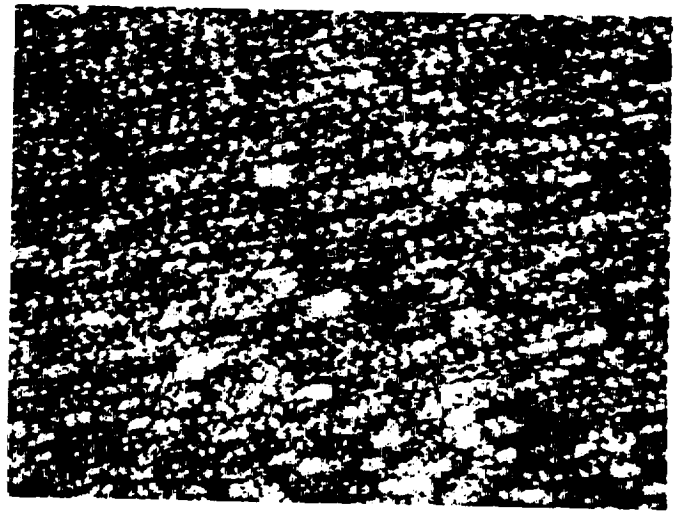
CORRELATION WINDOW

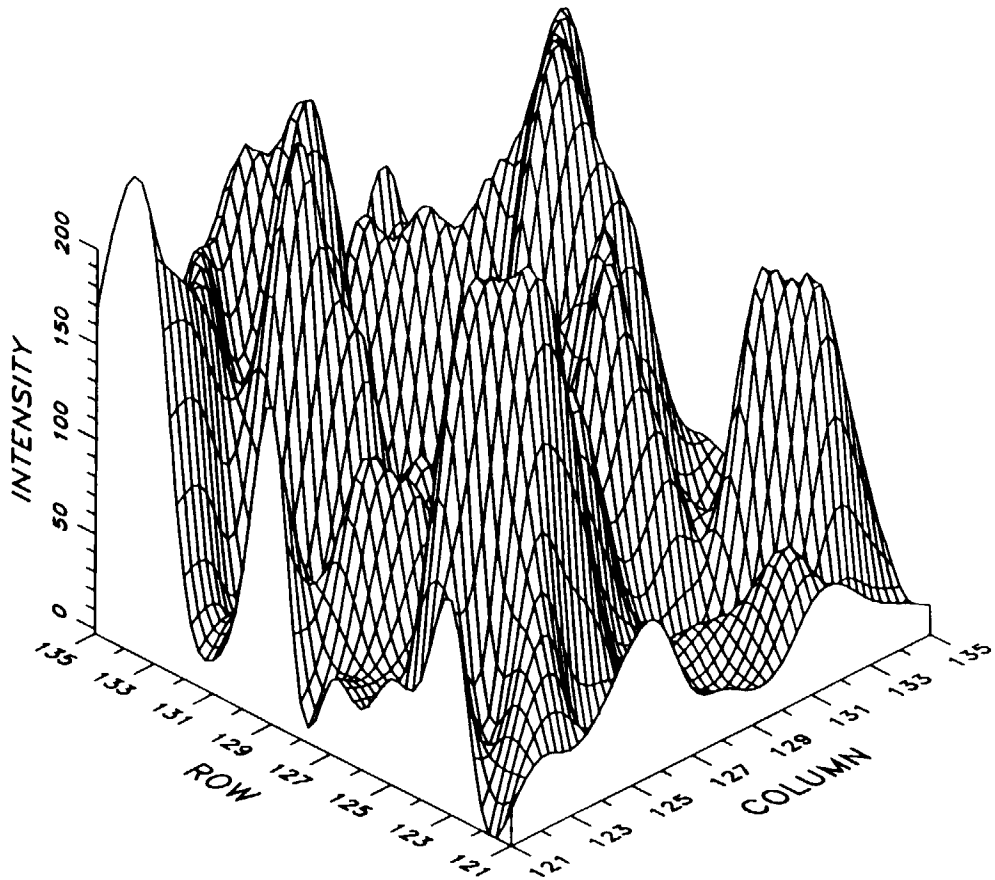

CORRELATION
0.8
0.4
0.0
-0.4
DIRECT VIEW
CORRELATION
0.8
0.4
0.0
-0.4
197
186
175
164
ROW
75
86
97
108
COLUMN
SEARCH REGION

APERIODIC RECORDING

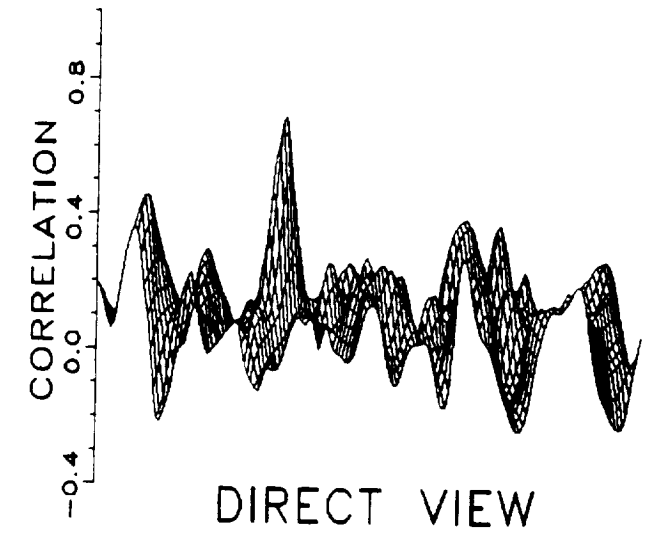




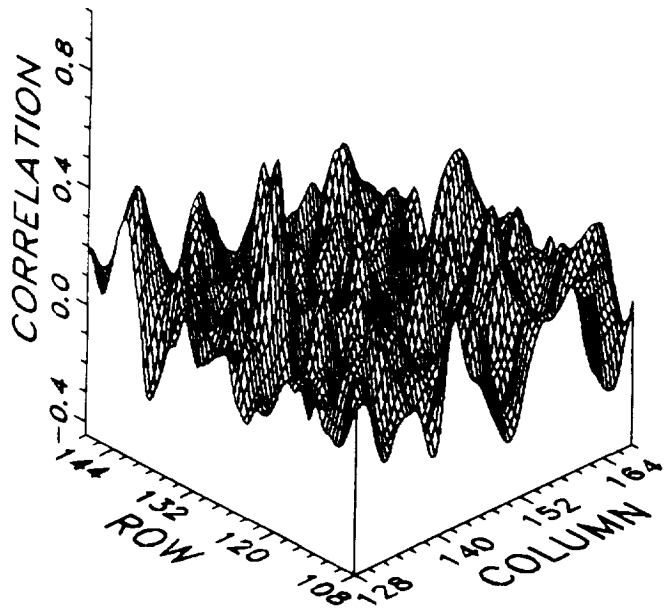




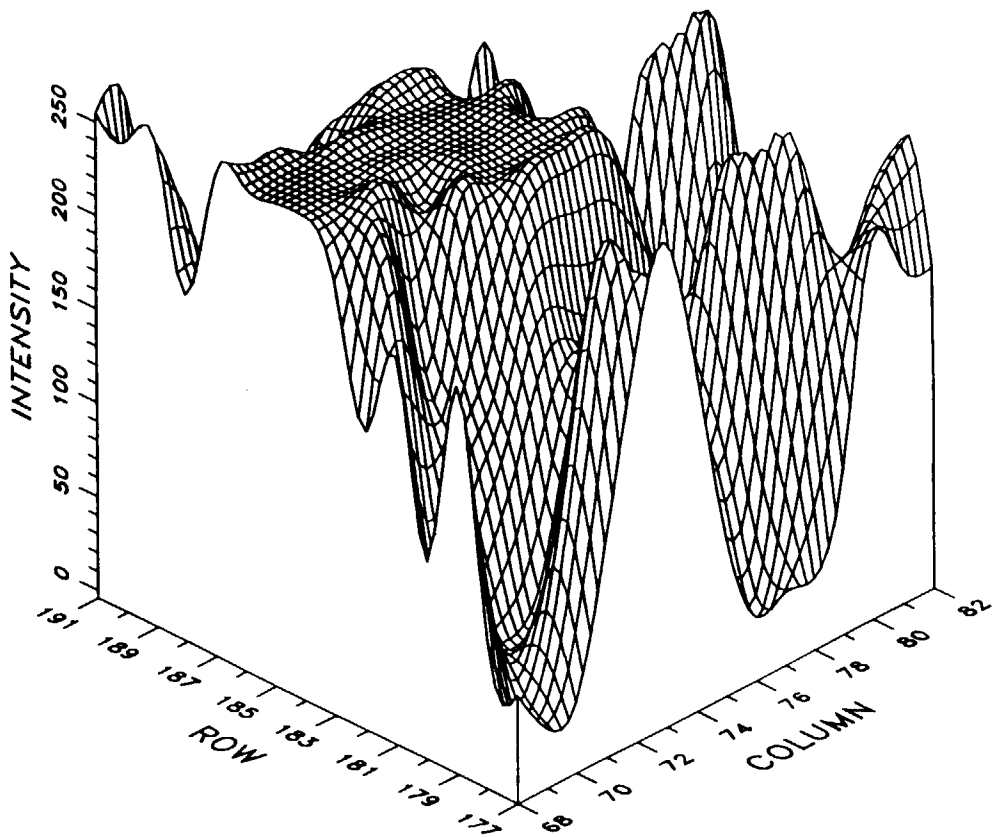
CORRELATION WINDOW



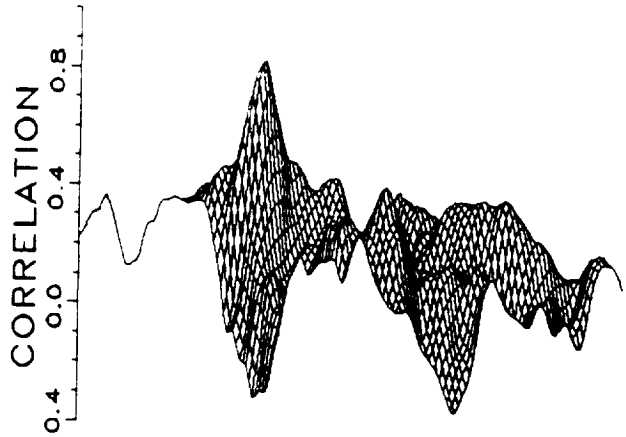
DIRECT VIEW



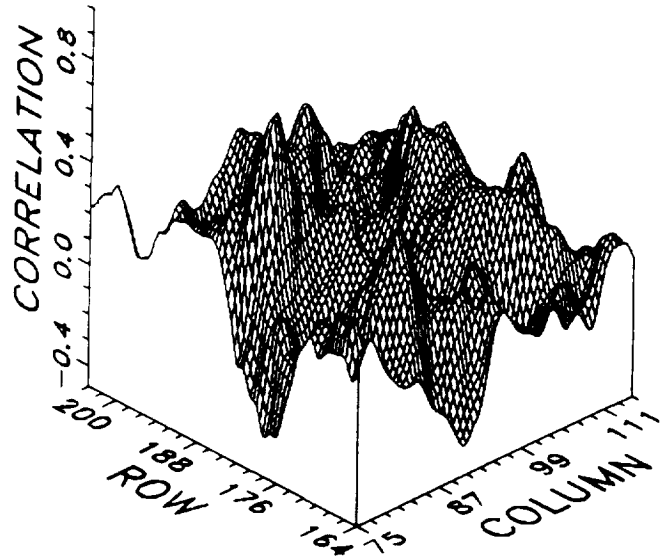
SEARCH REGION



CORRELATION WINDOW



DIRECT VIEW



SEARCH REGION

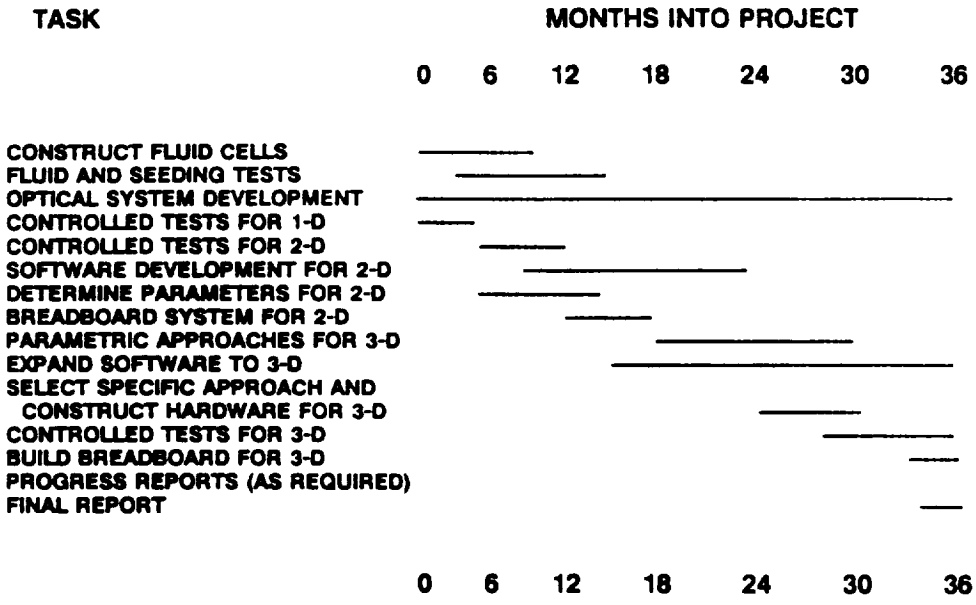
ADVANTAGES OF DIGITAL CORRELATION FOR FLUID VISUALIZATION

- FULL-FIELD MEASUREMENT TECHNIQUE
- REGISTRATION/INTERROGATION OF PHOTOGRAPHS NOT REQUIRED
- SIGN AMBIGUITY IN VELOCITY VECTOR ELIMINATED
- SPECKLE MOVEMENT LARGER OR SMALLER THAN SPECKLE SIZE
- POTENTIALLY FASTER THAN SPECKLE PHOTOGRAPHY
- RELATIVELY SIMPLE OPTICAL SYSTEM FOR DATA COLLECTION
- APPLICABLE TO WIDE RANGE OF SPECKLE SIZES
- IMAGES CAN BE ANALYZED WITH VARIABLE INTERFRAME TIMES
- DIGITAL OUTPUT COMPATIBLE WITH TELECOMMUNICATION LINKS

PRESENT PROGRAM STATUS

- HARDWARE PLATFORM SELECTED FOR FLOW MEASUREMENT
- SOFTWARE INSTALLED FOR IMAGE ACQUISITION, CORRELATION, AND GRAPHICS
- ILLUMINATION AND DETECTION SYSTEMS DESIGNED
- FLUID TEST CELLS DESIGNED AND CONSTRUCTED
- PRELIMINARY EVALUATIONS MADE ON FLUID AND SEEDING REQUIREMENTS
- MULTIPLE EXPOSURE CORRELATION TECHNIQUE INTRODUCED AND VALIDATED

TIMETABLE FOR THE TOTAL THREE YEAR PROJECT



OBJECTIVE FOR SECOND YEAR

PRODUCE A WORKING SYSTEM FOR 2-D VELOCITY MEASUREMENTS AND SELECT AN APPROPRIATE METHOD FOR MAKING 3-D VELOCITY MEASUREMENTS

TASKS FOR SECOND YEAR

- CONSOLIDATE HARDWARE AND SOFTWARE INTO A BREADBOARD SYSTEM THAT WILL MEASURE FLUID FLOW PARAMETERS IN 2-D
- PERFORM EVALUATIVE TESTS AND PARAMETRIC STUDIES OF THE DIFFERENT APPROACHES FOR OBTAINING 3-D DATA
- REVISE SOFTWARE TO CHARACTERIZE A 3-D VELOCITY FIELD